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Lunar Regolith Bagging System

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INTRODUCTION:

One goal of this project is to design a regolith container to be used as a fundamental building block in radiation protection of a habitable lunar base. Parameters for the container are its: size, shape, material, and structural design. The other goal is to design a machine to fill the regolith container which is capable of grasping and opening an empty container, filling it, closing it when full, and depositing it on the surface of the moon.

The most important constraint on the system was the total cost to be shipped to the moon. The cost of the entire operation is mainly due to the weight of the material being shipped. Obviously, the weight of the machine and the weight of the bags must be minimized. However, there are several other key factors to consider. The "brain" and moving parts of the machine must be protected and distanced from the loose soil. The time it takes to fill all of the bags should not exceed one daylight cycle on the moon, which is fourteen days. All materials must maintain its required properties between temperatures of -260 and 260 degrees F. The rocks on the moon are razor sharp because there is almost no atmosphere to erode the corners. The bags must be made extra strong to prevent puncture or tear and must survive beta and UV radiation. (Gamma radiation is almost identical to that on earth, so it is ignored). The closing mechanism in the bags must not fail when the bag is being deposited or lifted by another machine.

DESIGN STRATEGY

Originally focusing on the problem of creating a large number of bags filled with regolith, this problem was broken down into two district tasks: designing the bag and the fabric itself, and designing a mechanism to fill the bags with regolith, seal the tops, and drop the bags off for future placement onto the lunar habitat.

Each subteam developed a series of design criteria to evaluate the proposed designs and narrow the options to one combined choice.

In this report, the alternatives considered for each part of the design will be discussed. The design of the Lunar Regolith Bagging System will then be presented.

ALTERNATIVES: BAG AND FABRIC CONSIDERATIONS

I. Material Alternatives

The material or fabric desired for application in space must be suitable for the space/lunar environment. These constraints include:

* The material must be either resistant to or transparent to electron (β) radiation, which is the predominantly degrading type of lunar radiation.

* The material must be resistant to vacuum ultraviolet (UV) radiation.

* The material must have a service temperature range that corresponds with lunar temperatures (-250 F to 250 F).

* The material must be able to withstand extreme temperature swings, such as those experienced on the moon without melting or becoming brittle.

* The material must be cut- and puncture-resistant since razor sharp rocks will be bagged and the bags may be pulled across the lunar surface, which could puncture or tear the material.

* The fabric must be lightweight in order to minimize the overall weight transported in the earth-to-moon shuttle craft.

* The price per yard of the material, although not critical in comparison with the price of transportation, is important in calculating the entire cost of the project since the fabric is high performance in nature and a large number of bags will be constructed.

In determining a suitable material for this design, both organic and inorganic materials were considered. The organic material included PBI in a 50/50 blend with p-aramid, Nomex, Teflon TFE, Spectra 900, and Kevlar 149. Inorganic materials that were considered include fiberglass, Nextel

ceramic, and a general category of metals. Paper forms were also considered in which Nomex (organic) and Nextel (inorganic) were included.

Among the organic materials, Hoechst Celanese polybenzimidazole (PBI) 7.5 oz/sq. yard fabric was considered because it is a high performance fiber with a unique combination of properties. PBI, when combined in a 50/50 blend (PBI/p-aramid), offers the best combination of temperature resistance, puncture resistance and tensile strength. PBI has good high temperature dimensional stability and is will not melt, drip, or become brittle, which suggests that it has the high temperature requirements needed (Hoechst Celanese Corporation, 1989). However, no information was available giving the low temperatures that the material can withstand. Finally, PBI was not chosen because specific information stating whether it is resistant to or transparent to either ultraviolet or electron radiation is not available.

Nomex, produced by DuPont, was considered because of its excellent range of temperature stability and its resistance to cutting (DuPont, 1978). Nomex was not chosen, however, because of the lack of available information on its specific tensile strength. According to Dr. Bill Percival of DuPont, the Nomex would degrade upon contact with electron (β) radiation.

Spectra 900, which is produced by Allied-Signal Corporation, was considered. The Spectra was rejected due to the lack of information available on its resistance to or transparency to electron radiation (Bill Burton of Allied-Signal, 1990).

DuPont produced Teflon TFE fluoropolymer was considered since its service temperatures were within the range needed for this application (DuPont, 1968, 1989). However, the Teflon TFE was not cut resistant when tested in the physical testing laboratory of the School of Textile and Fiber

Engineering at Georgia Tech (Appendix A). Additionally, Teflon TFE would degrade rapidly when exposed to electron radiation according to Dr. Bill Percival of DuPont.

Kevlar 149, also from DuPont, offered high strength, high toughness, high wear resistance, low density, and high temperature stability. Kevlar 149 does not melt or soften, has good dimensional stability and offers a long product life (DuPont, 1989). Dr. Paul Riewald of DuPont Industrial Applications Research has completed studies (Appendix B) confirming that Kevlar will not degrade under constant UV exposure in the absence of oxygen. For the general purpose of this project, according to Professor J. W. Brazell of the Mechanical Engineering Department at Georgia Tech, the conditions on the moon resemble a "near complete" vacuum. Dr. Riewald further stated that Kevlar is transparent to electron radiation.

Among the inorganic materials under consideration, fiberglass fabric was initially considered because it is resistant to vacuum UV radiation and transparent to electron radiation according to Dr. John L. Lundberg of the School of Textile and Fiber Engineering at Georgia Tech. The service temperatures specified for the fiberglass cover the range required for lunar applications according to information obtained from the Clark Schwebel Fiber Glass Corporation. The fiberglass was rejected, however, because its level of cut resistance was less than that determined necessary (Appendix A).

3M brand High Performance Nextel 312 ceramic material was considered because it offered a long product life, very high temperature stability, resistance to vacuum ultra violet radiation as well as resistance to electron radiation (3M, 1988). The cut resistance of the Nextel fabric was poor, however, causing the Nextel to be rejected (Appendix A).

A general category of metals were considered, were ruled out because of the greater density of the metals in comparison to the Kevlar 149.

A coating (film) or resin was considered in order to give protection from radiation and cutting or puncture to the fabric. Only organic films and resins were considered as there are not inorganic films or resins.

Teflon FEP - fluoropolymer, made by DuPont, does not melt and is good for unspecified high temperatures, according to available literature. The FEP is not cut resistant, nor is it resistant or transparent to electron (β) radiation.

Teflon PFA is also made by DuPont. The PFA service temperature is good for the lunar application. However, it is not cut resistant, nor is it resistant or transparent to either electron or vacuum ultraviolet radiation.

Tefzel fluoropolymer has a service temperature range that is also good for the lunar application, but like the Teflon PFA, it is not resistant or transparent to vacuum ultraviolet or electron radiation (DuPont, 1988). It is not cut resistant either.

A coating (film) or resin was not chosen due to inadequate information currently available. Information provided by Dr. Paul Riewald, senior research associate at DuPont (Appendix B), did not specify a particular type of film or resin that would be applicable as a protective coating for this design. More research must be conducted in this area before a recommendation may be made.

II. Fabric Structure Alternatives

The fabric structures considered were knit, woven, and paper/nonwoven.

A knit fabric is relatively lightweight, but it was not deemed appropriate for rough usage applications such as the lunar bag design. Upon stretching, the a knitted structure may become porous, allowing more than the acceptable amount of regolith to leak out. In the event that ripping or tearing should occur, the knitted fabric would continue to ravel catastrophically.

Nonwovens and papers were deemed inappropriate as well, primarily because very little experimental performance data is available for these structures. The nonwoven structures of Nomex and Nextel have high tensile strength, sufficient service temperatures, and long service lives (up to 10 years or more). The nonwoven structures made of high performance Nomex fibers are significantly more expensive than the knitted or woven structures, according to the Nomex marketing department at DuPont. Nomex paper was not chosen because it is not resistant to either vacuum ultraviolet or electron radiation. Nextel paper was not chosen because it has poor resistance to puncture and only fair resistance to cuts.

A woven structure was considered and chosen because it had the least stretch capability and the least porosity. Also, a weave can be designed to prevent propagation of rips throughout the rest of the fabric.

There are many types of weave structures that are used in high performance products, including the twill, the satin, the plain, and the rip-stop weaves. In choosing a weave structure suitable for the lunar bag design, the most important consideration was the ability of the weave

structure to prevent the propagation of rips or tears. By reducing the size that a rip or tear may become, the severity of the rip is reduced, and the leakage due to the rip may be kept to a minimum.

The twill weave produces the structure shown in Figure 1a, and is commonly used in the manufacture of denim in the apparel industry. The twill weave does not have the capability to prevent the propagation of rips from destroying a fabric, so the twill weave was rejected.

A plain weave, shown in Figure 1b, was considered because of its widespread use in high performance applications, such as fire-proof garments, cut-proof chaps for use with chain saws, bullet-proof vests and helmets (DuPont, 1989). The plain weave does not have the capability to prevent rip propagation either, and was rejected.

The satin weave, shown in Figure 1c, has less dimensional stability than either the plain or the twill weave. The satin weave can be constructed to obtain a specific amount of drape, which is why it is often used for formal dress fabrics (Joseph, 1986, 225). The satin weave also does not have the ability to prevent rip propagation and was rejected because of this.

The rip-stop weave, shown in Figure 1d, is commonly used in applications where the prevention of rip propagation is desired, and sometimes critical. The rip-stop weave is found in parachutes where propagating rips mean death. The rip-stop weave was chosen as the desired weave structure for the regolith bag design.

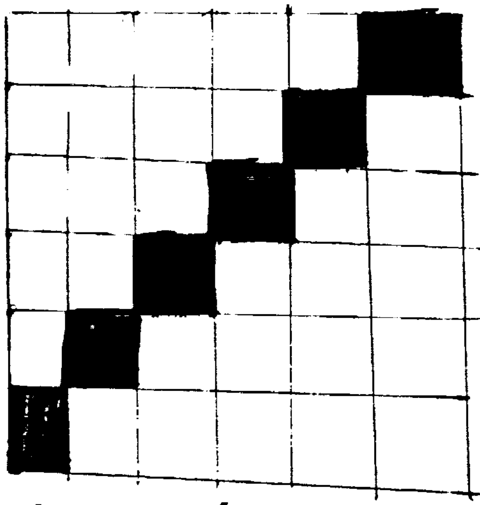

Fig 1a - twill weave

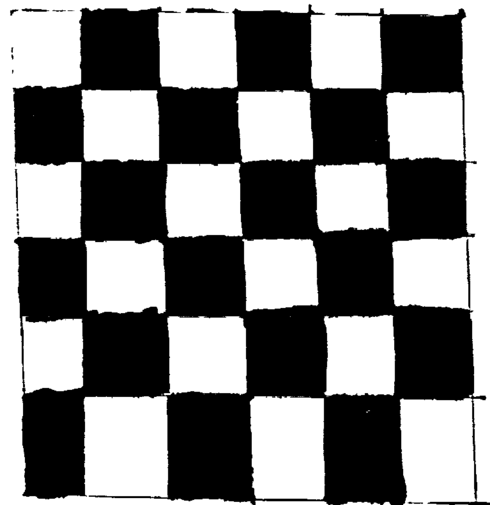

Fig 1b - plain weave

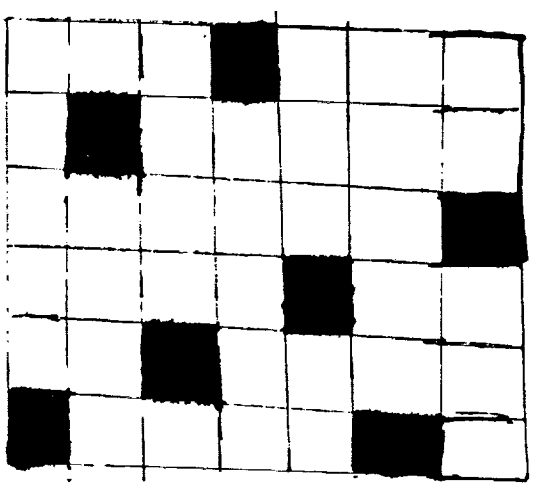

Fig 1c - satin weave

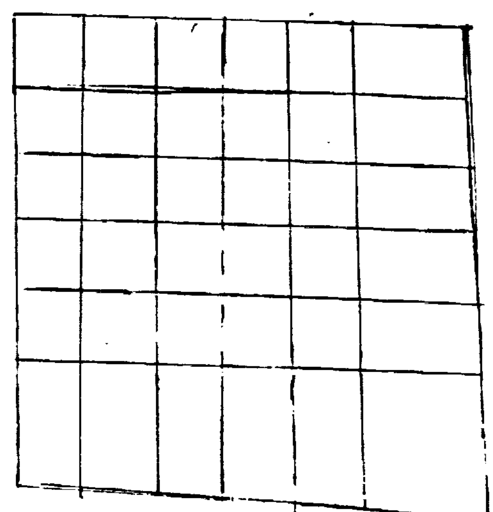

Fig 1d - ripstop weave

III. Bag Shape Alternatives

In designing the shape of the regolith container, several assumptions and design parameters were considered to be important. First, it was assumed that a maximum volume of regolith per container was desirable for protection of the habitat against radiation, as well as to minimize the amount of containers needed. Secondly, it was assumed that a stitched seam in the construction of the containers could be considered an area of potential weakness because the thread used in stitching the seam would be most vulnerable to cuts from the regolith. Finally, it was assumed that, due to the fabric overlap required for a seam, a seam would weigh more per length than the container would. From these assumptions, the parameters of the container shape were derived. The design parameters are as follows:

* The regolith packing potential (the ratio of the volume of the regolith per the volume of the free or unfilled space) of the container must be as near to ideal (∞) as possible. From the packing potential, the maximum volume of regolith per bag weight can be developed.

* The number of seams in the container design must be held to a minimum in order to minimize potentially weak areas and prevent additional weight added to the container.

* The shape of the regolith container must be applicable to the regolith bagging machine design.

Initially, two categories of container shapes were considered: structured shapes, those with specified corners and angles necessary to the design; and unstructured shapes, those without specified corners or angles. The structured shapes included a box-shaped pillow, a shoe box with separate cover, a grocery bag with a rectangular bottom and sides

perpendicular to each other, and a pyramid- or trapezoid-shaped container with the base wider than the top. (Figure 2) The unstructured shapes included a pillow case, a tube sock, a come, a bread bag, a bag with vertical accordion pleats, and a "pie pocket"or container with flat top and bottom, similar to the top and bottom pie crusts, which would be secured together after putting regolith between them like the filling in a pie. (Figure 3)

Upon inspection of the geometries of the shaped in both categories, it was determined that the unstructured shapes had better potential for maximum regolith packing -- a higher ratio of regolith volume to free volume in the container. The unconstructed shapes required fewer seams for the construction of each shape than the structured shapes required. The structured shapes were rejected based on their poor comparison with the unstructured shapes in terms of both the regolith packing potential and the number of required construction seams.

After comparing the geometries of the unstructured shapes, it was determined that the cone did not have a good regolith packing potential. Specifically, if a larger rock were to be scooped into the cone first, the rock would prevent smaller pebbles and soil from filling the free volume of the tip of the cone as shown in Figure 4. On this basis, the cone shape was rejected.

The pie pocket model was rejected because its concept of forming a sealed shape after filling is applicable to only one of the filling machine designs under consideration, and this design was ultimately not chosen.

The accordion pleated bag does not offer an increase in the packing potential over the pillowcase, sock or bread bag. Instead, the accordion pleated bag requires special methods of construction and storage. The

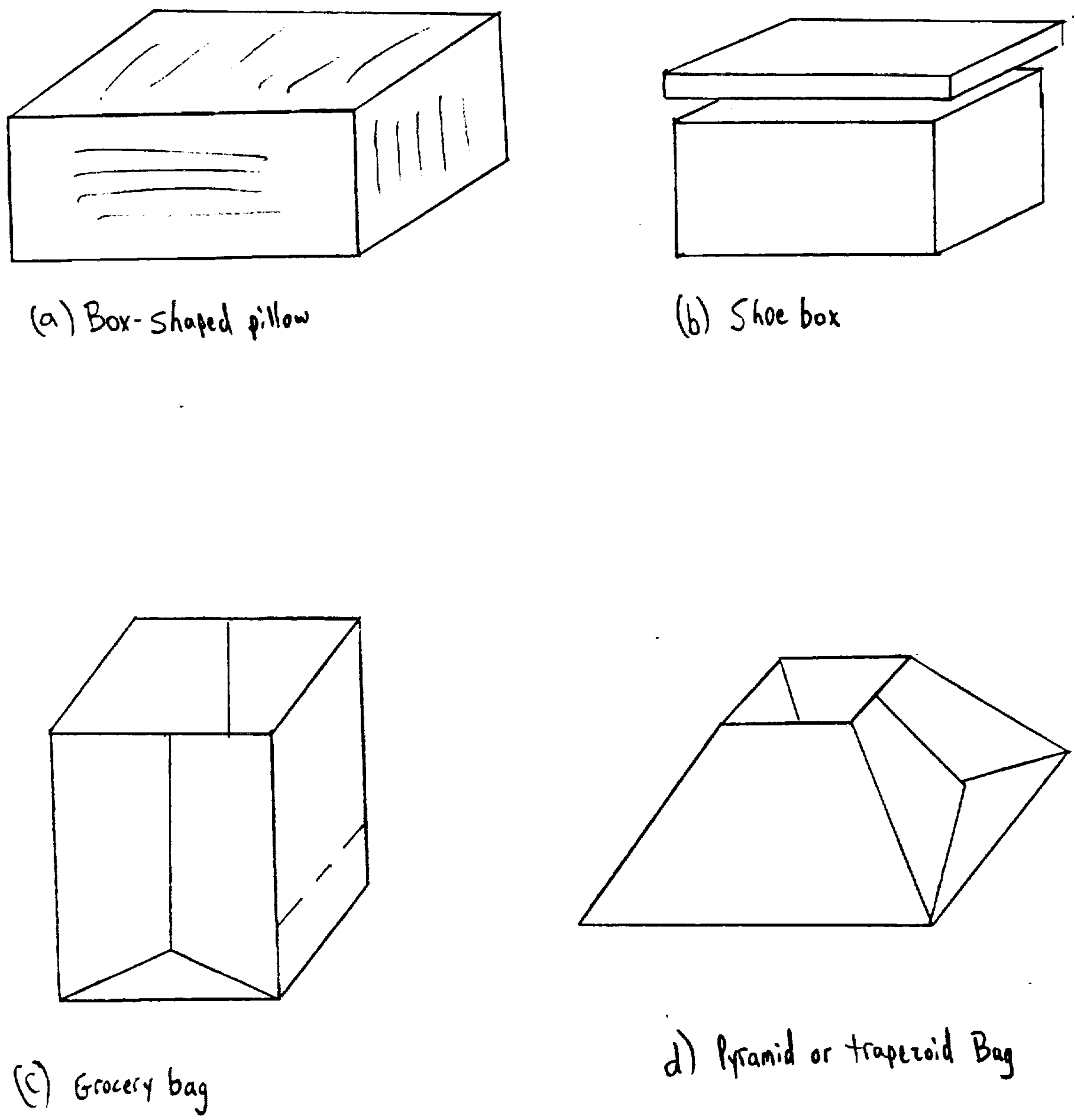

FIGURE 2: Structured Bag Shapes

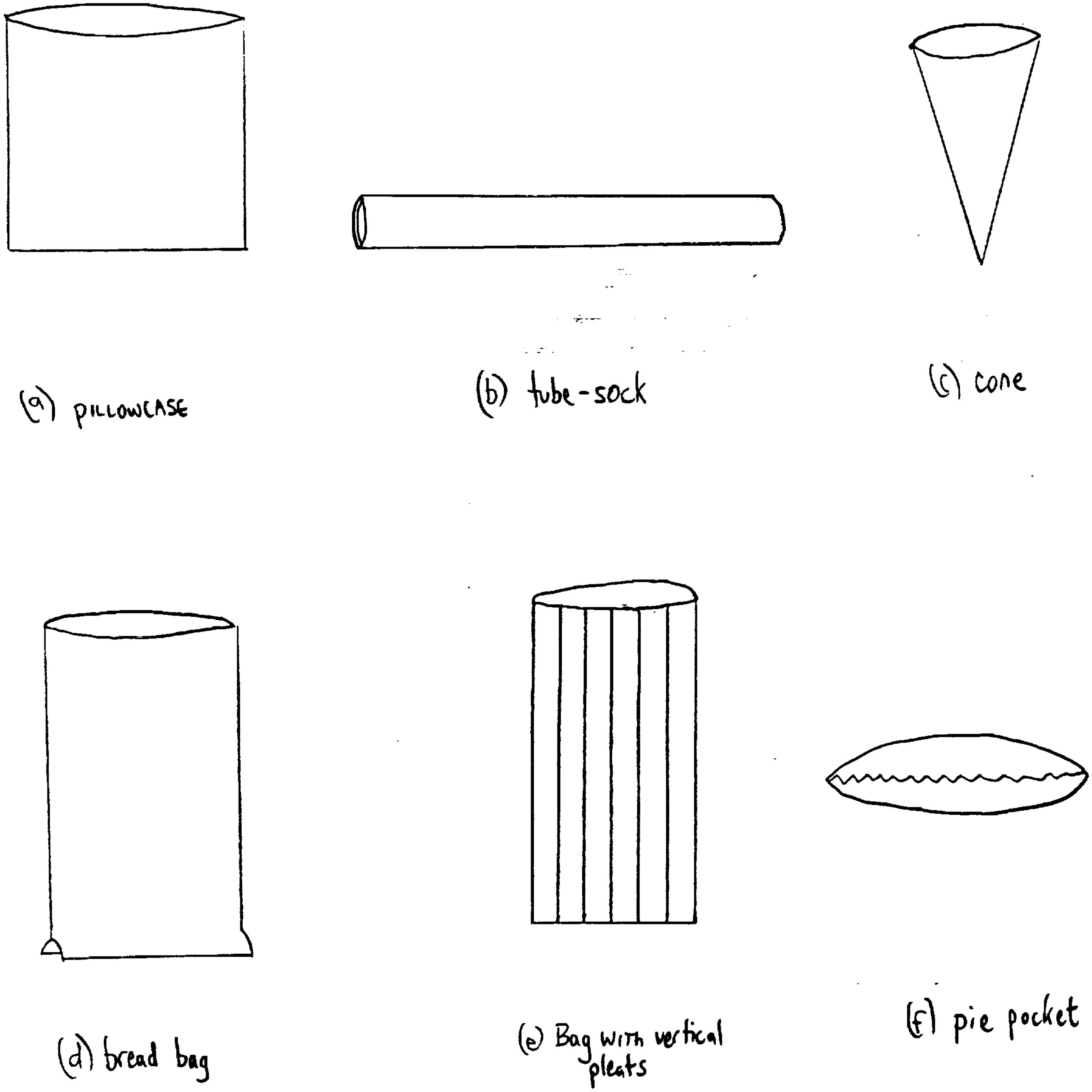

FIGURE 3: UNSTRUCTURED BAG SHAPES

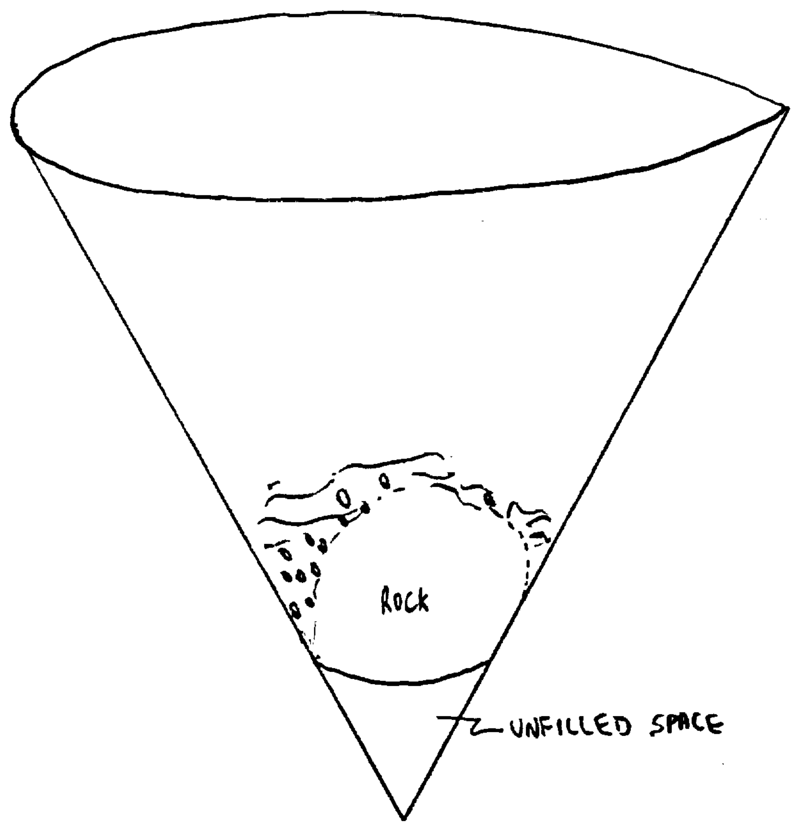

FIGURE 4: DEMONSTRATION OF THE POOR PACKING POTENTIAL OF THE "CONE-BAG"

accordion pleated bag was rejected in favor of simpler shapes that accomplished the same objectives.

The tube sock model requires the least amount of construction seams of the three remaining alternatives. However, the tube sock requires only one seam during construction because the fabric structure of the sock is that of a circular knit. The fabric structure desired for this design application is that of a weave, and therefore, the tube sock model could not be used.

The two remaining alternatives, the pillowcase and the bread bag, were compared and contrasted with regard to their maximum regolith packing potential and to their design simplicity, i.e., the number of seams required in construction.

Both the pillowcase and the bread bag utilize a rectangular piece of fabric, which is doubled over and stitched across the bottom and up the side to form the general rectangular shape of each container. If the initial pieces of fabric for the pillowcase and the bread bag are the same size, the surface area of the pillowcase would be equal to that of the bread bag. Since the total weight of the fabric is directly proportional to the surface area of the bag, the weights of the pillowcase and the bread bag would be equal.

The pillowcase model, when empty, resembles a rectangle. When filled as shown in Figure 5a, the pillowcase volume would approximates a cylinder (Appendix C).

The bread bag model requires two small tacking stitches of negligible weight to tuck the corners of the bag up, in order to form the inverted pleat across the bottom of the bag that is visible when the bag is empty as in Figure 5b. When filled, the bread bag volume approximates a cylinder minus two small triangular volumes at the base where the corners of are tacked up. (Appendix C)

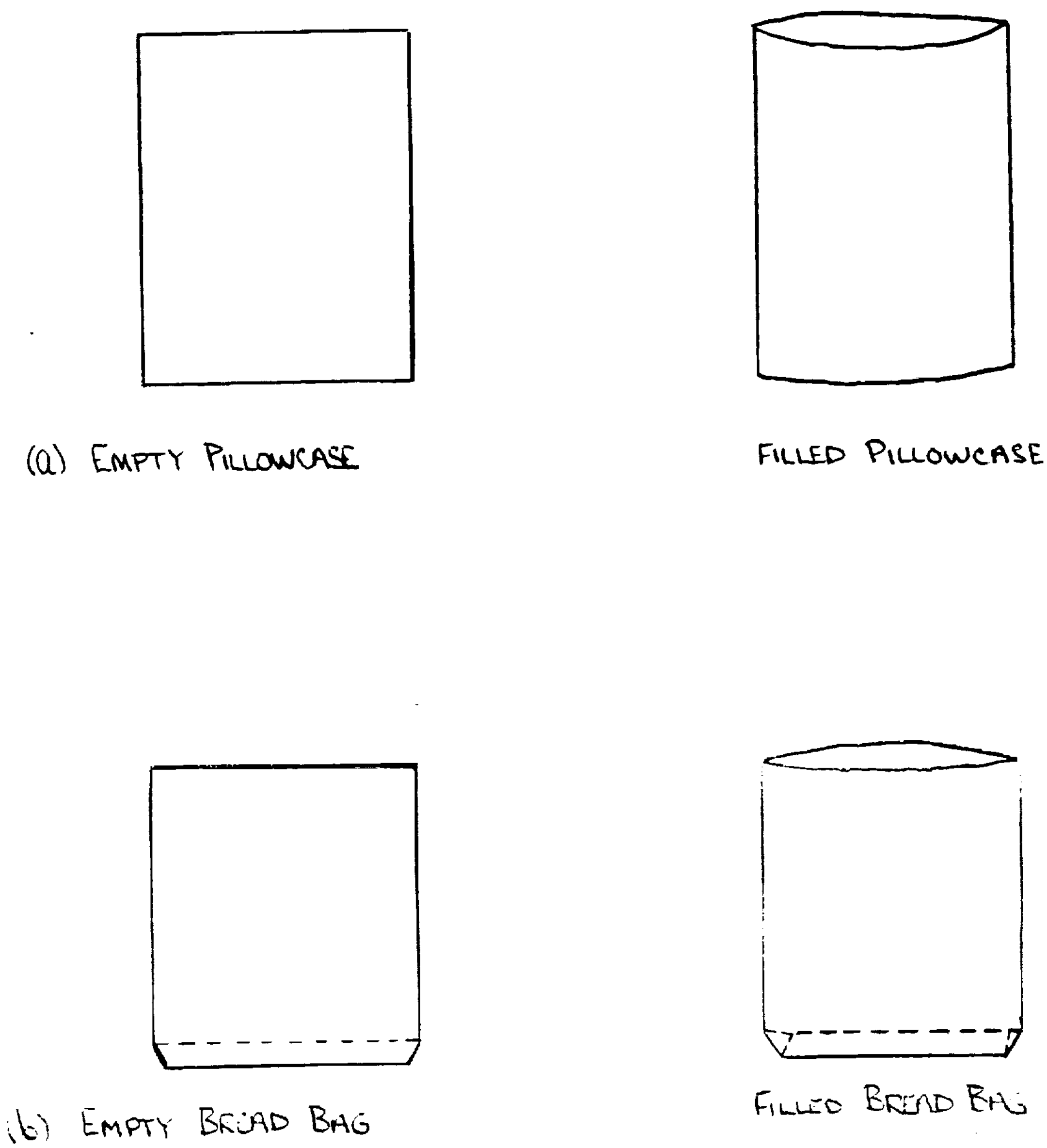

Figure 5: Empty and Filled Shapes of (a) the Pillowcase and (b) the Bread Bag

The slight loss in volume in the bread bag compared to the volume of the pillowcase causes the regolith packing potential of the bread bag to be slightly less than that of the pillowcase (Appendix C).

The bread bag model incorporates an extra step of tacking up the corners in order to obtain a pleat at the bottom of the bag. This pleat theoretically allows the regolith to form a flat base at the bottom of the bread bag. Since, in the chosen bag-filling machine design, the container is to be filled while in a horizontal position, the base pleat in the bread bag does not offer an advantage over the simpler pillowcase. Therefore, the pillowcase was determined to have the maximum regolith packing potential and the simplest design requiring the fewest number of seams, yet while remaining applicable to the design of the regolith bagging machine.

IV. Bag Size Consideration

It was necessary to assume a constant bag shape for the ideal bag size to be found. The pillowcase bag shape, described in the previous section, was used for the idealization. Also, for idealization, the top section of the bag that is used in the closing mechanism was neglected. The bag size idealization found the optimum bag dimensions necessary to obtain the desired ratio of fabric weight to regolith weight.

The bag size was idealized by finding the volume of the bag fabric, assuming a constant fabric thickness and comparing the fabric volume to the maximum filled volume of regolith attainable for a range of bag widths from 6 to 60 inches. The length of the bag was held constant because the first derivatives of the equations for both the volume of the bag fabric and the volume of the regolith showed that these equations depend upon the width and not the length for change. A ratio of the regolith volume to the bag fabric volume was calculated. This ratio was plotted against the width of the bag. The ideal bag width was calculated from this graph. The maximum regolith weight that the bag fabric could withstand on the moon was calculated, and was found to be much greater than that of the regolith volume. (Appendix D)

The data for the ideal bag size is summarized below:

width: 36 inches
length: 72 inches
thickness: 7.57 mils

volume of bag fabric: 39 cu. inch
maximum regolith volume: 29702 cu. inch
bag mass / regolith mass ratio: 0.001554
total bag mass(fabric+regolith): 1289.08 pounds

From this data, the minimum number of bags required to cover the lunar habitat with a minimum thickness of two meters of regolith would be 924 bags. Twelve bundles of bags would be needed if each bundle contained 80 bags. (See calculations in Appendix H)

V. Bag Storage Alternatives

In choosing a method of bag storage, several design parameters had to be carefully considered. The most important of these parameters was the applicability of the method to the regolith bagging machine. Other parameters included the ease of bag withdrawal from the bundle, the degrees of freedom required by the machine to load the bag and to move into position for filling the bag, the occurrence of permanent deformation of the bag as a result of the storage method, the ability to store a maximum number of bags per bundle volume and the need for packaging aids (centers or containers) to promote uniform bag storage.

The bag storage options that were initially considered were (Figure 6):

* computer paper -- folded with connected ends
* Kleenex® facial tissue -- folded with staggered ends
* toilet paper roll -- rolled with connected ends
* garbage roll -- roll with staggered ends
* "Dixie Cup" stacks -- stacked one inside another
* horizontally stacked like copy machine paper
* vertically stacked like the pages of a book on a shelf
* vertically stacked with tops connected in a series like paper dolls

Neither of the vertically stacked options were applicable to the chosen design of the regolith bagging machine and were rejected.

The withdrawal of and loading of the bag from a storage in computer paper stack, a toilet paper roll, a or flat horizontal stack onto the bagging machine was determined to require too many degrees of freedom of the loading mechanism to be useful in the mechanical design. These options were rejected on that basis.

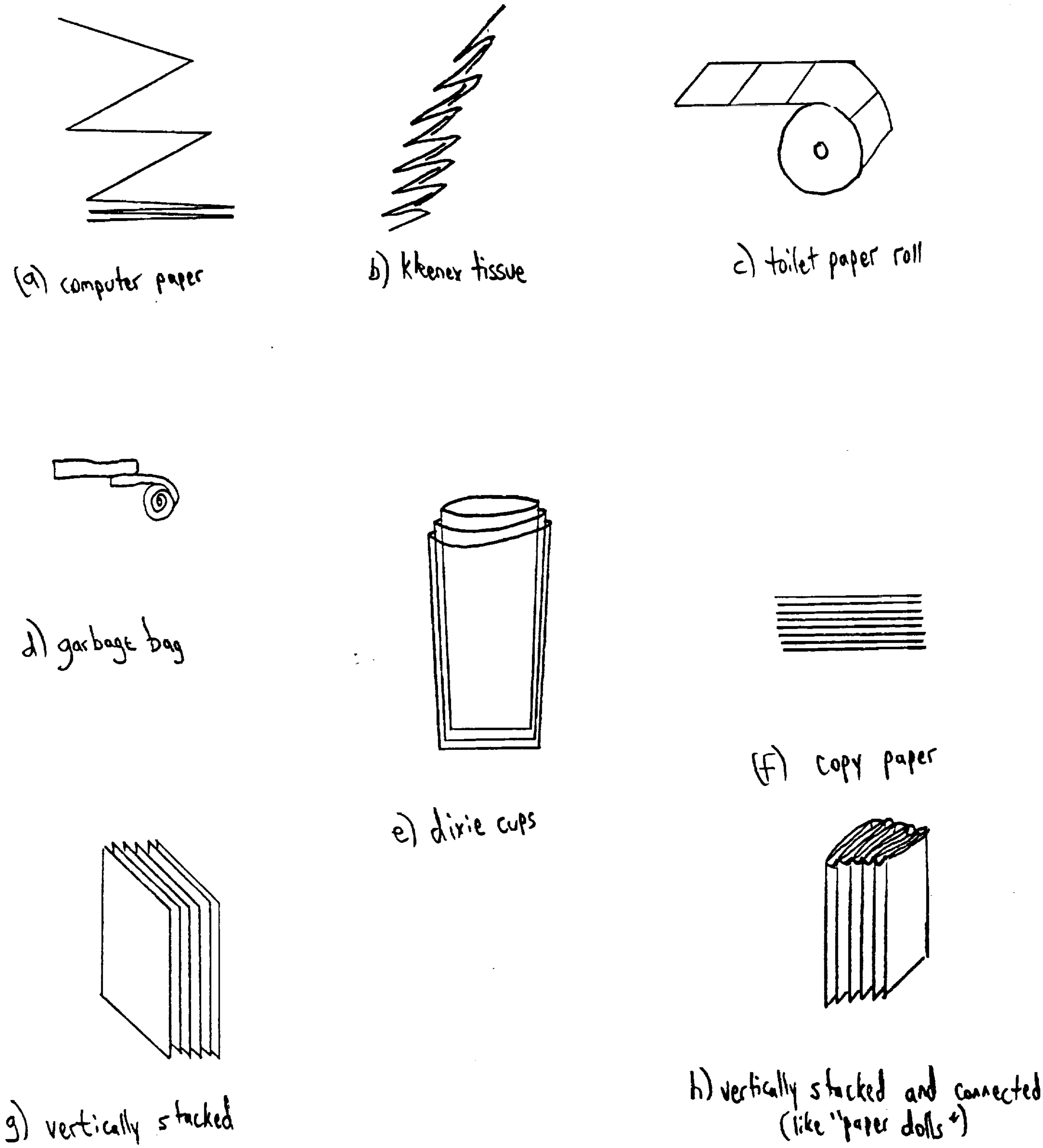

FIGURE 6: BAG STORAGE OPTIONS

The unconnected tissue storage option was rejected because it requires a box or other container into which the bags may be stacked.

The remaining alternatives, the staggered roll and the Dixie cups were considered. The Dixie cups were chosen over the staggered roll because the staggered roll option depended too heavily on precise staggering when construction the bundle. As the roll unraveled and the diameter of the roll decreased, the opening of each newly exposed bag would be difficult to pinpoint with the accuracy required by the remote-controlled bagging procedure used in the design of the bagging machine. The Dixie cup option could be relied upon more heavily, because as one bag was withdrawn, the next bag was exposed in the correct position (Figure 7).

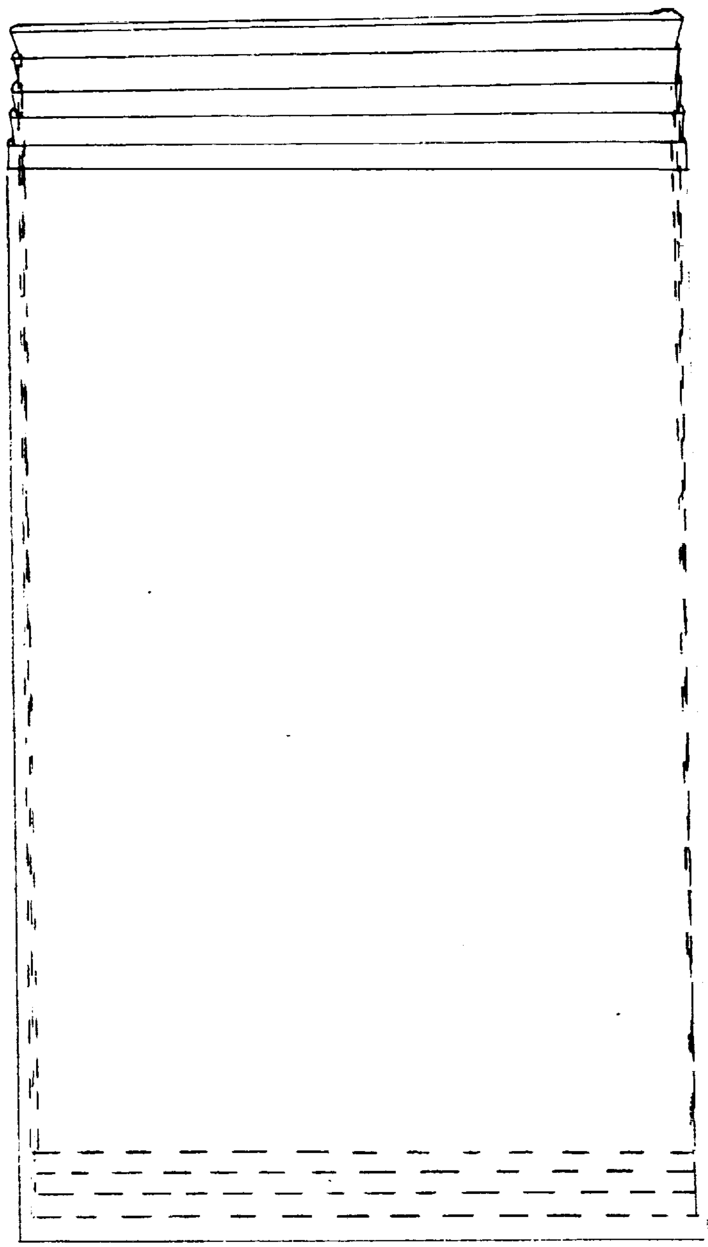

FIGURE 7
"DIXIE CUP" BAGS

FASTENING ALTERNATIVES

Many fascinating ideas were created to close the regolith-filled bag. Common fastening means were modelled to determine if they were applicable to the moon's surface. These include Ziplock, Velcro, drawstring, twist-tie, rubber-band, zipper, clothespin, snaps, staples, and many others. The tests they had to pass were:

Applicability to the machine design,
Short term reliability,
Temperature limitations,
Machine's degrees of freedom required,
Leakage rate,
Fastener Mass,
Material Limitation, and
Long term reliability.

The option with the greatest number of positive marks was the magnetized thread design. (See Appendix G. for the list of fastening means and the decision matrix).

ALTERNATIVES: MECHANICAL CONSIDERATIONS

The basic objectives in designing the bag-filling machinery were to create a system to pick up a bag, open the bag, fill the bag with lunar soil, close the bag, drop it, and then start the process all over again with the next bag. The system should be controllable by remote signals from earth, and should minimize the possibility of breakdown because astronaut time spent on the moon costs approximately $80,000 per hour (according to Mr. Brazell of the M.E. department of Georgia Tech). Also, the machinery should be as lightweight as possible because each pound transported via the space shuttle costs approximately $20,000 to ship (according to Mr. Brazell). Finally, because cubic space aboard the shuttle is limited, the total volume of the system should be minimized.

The following mechanical alternatives were considered in meeting the objectives of the bag-filling system:

* a platform/brush combination;
* a forced ramp;
* a conveyor belt system;
* a"Pac man" or double clam shell scoop;
* an imbedded cone and brush;
* a screw lift;
* a paddle wheel with shroud;

* a "french fry scoop".

In order to evaluate these options further and form a basis of comparison among them, several design parameters were identified, including a minimal number of moving parts exposed to the disruption of dirt produced by any of the mechanisms, a good bag closure system, a good control system capability, and the avoidance of specific bag shape constraints.

The platform/brush combination, shown in Figure 8(a), was designed for attachment on a lunar vehicle which moves in an up-and-down motion, such as a Skitter. When the Skitter is "down", the bottom "crust" of a pie pocket is dropped onto the flexible platform, dirt is swept by the two brushes into the center of the crust until a weight sensor in the platform indicates the crust is full, and then an upper crust drops on to the top of the regolith pile and lower crust. All edges of this pocket must be sealed with either a pressure sealing mechanism (velcro, staples, etc.) or an adhesive (glue, etc.). When the Skitter raises to take another "step", the filled pocket slips off the flexible platform and onto the ground to await pickup and placement on the habitat. However, because lunar dust was to be swept over the sealing surface, the potential for dirt to interfere with a tight seal was significant, and the design was rejected for this reason.

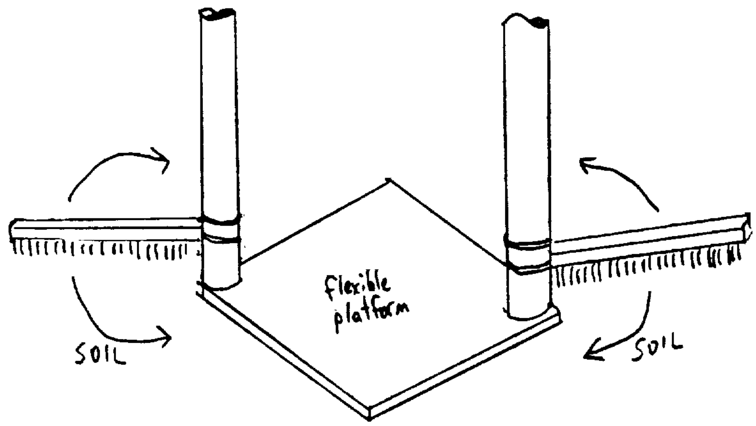

FIGURE 8(a).

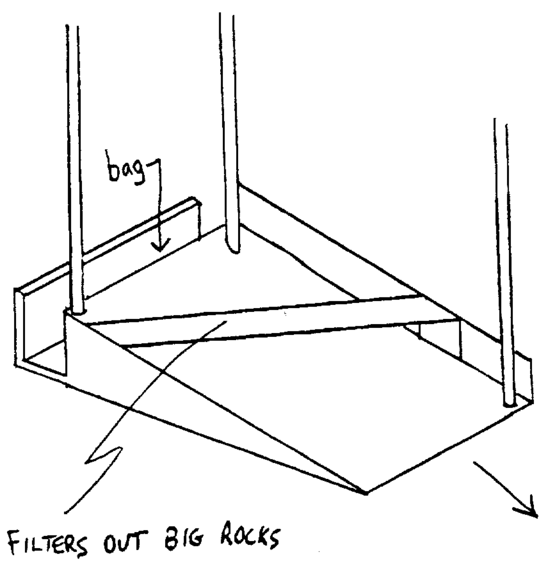

FIGURE 8 (b)

The forced ramp, shown in Figure 8(b), is designed for attachment on a lunar truck, or other vehicle that moves in a horizontal direction over the moon's surface. As the ramp is forced in a forward motion through the dirt approximately 2-3 inches below the surface, the dirt's own inertia forces it up the shallow ramp where it drops into a vertically placed bag resting on a platform. When a weight sensor underneath the bag indicates the bag is full, the platform supporting it drops, and the bag is closed using its own weight and a drawstring closure top. Unfortunately, in testing this design on earth, it was discovered that the inertial forces would only push the dirt up a short ramp, leading to usage of a comparatively shallow bag. The maximum bag size that could be used in this design was not in the range of ideal bag sizes previously determined. Although the simplicity of the design indicated a resistance to mechanical breakdown, the forced ramp design alternative was rejected due to its dependance on a specific bag size that was not ideal.

The conveyor belt, sketched in Figure 9(a), provided a way to raise the dirt to any level, thereby eliminating any dependence on a specific bag size or shape. The conveyor belt design also could utilize an effective control system to determine when filling should stop and sealing should begin. However, this option resulted in a large number of moving parts near the soil required to move a bag into place and seal the bag. One of

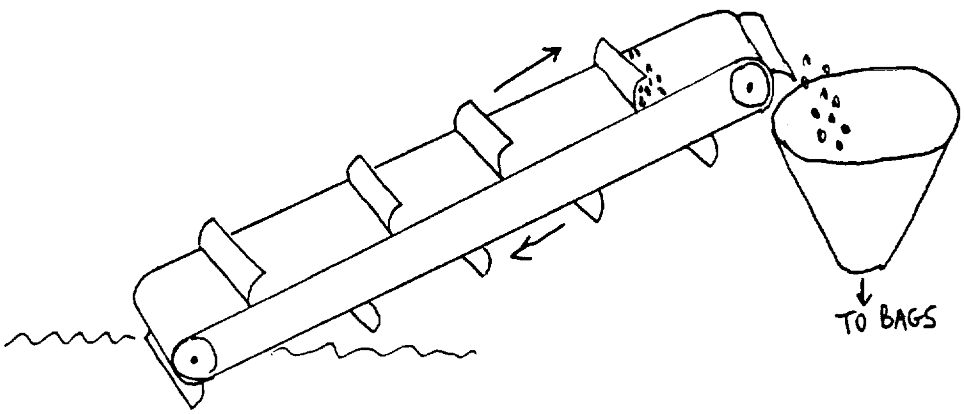

FIGURE 9(a)

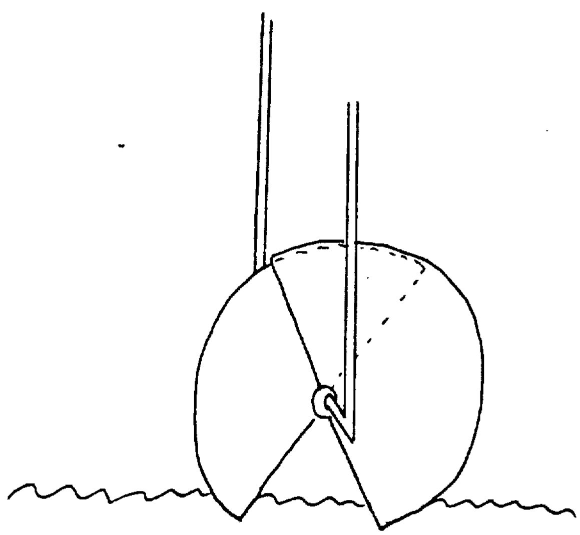

FIGURE 9(b)

the most significant design criteria was a consideration for the potential for breakdown, and a large number of moving parts increased that potential, especially if the moving parts are exposed to ambient regolith clouds created during the filling process. The conveyor belt option was rejected on that basis.

The "Pac man"/double clam shell, shown in Figure 9(b), was also rejected on the basis of the multiple moving parts criterion. The mechanism depended heavily on the ability for two interlocking parts to come together forcibly with a fairly tight seal around the dirt, then pivot to a position above the vertical bag, and release the dirt. The potential for clogging any of the sliding parts was too significant to be ignored.

The imbedded cone, pictured in Figure 10(a), was a unique design in that, instead of raising the dirt to a position above the ground to fill a vertical bag, the bag was inserted into the cone and forcibly imbedded into the moon's surface. A bag was dropped from a bag bundle holder into the open cone below, then dirt was swept into the cone and bag combination. However, the surface of the moon presented an uncontrollable parameter. While the surface of the moon is loosely packed for approximately the first six inches, the subsurface then starts to become more dense quickly. In order to penetrate that dense packing, a very strong material must be used in constructing the cone and it must be imbedded at a substantial force,

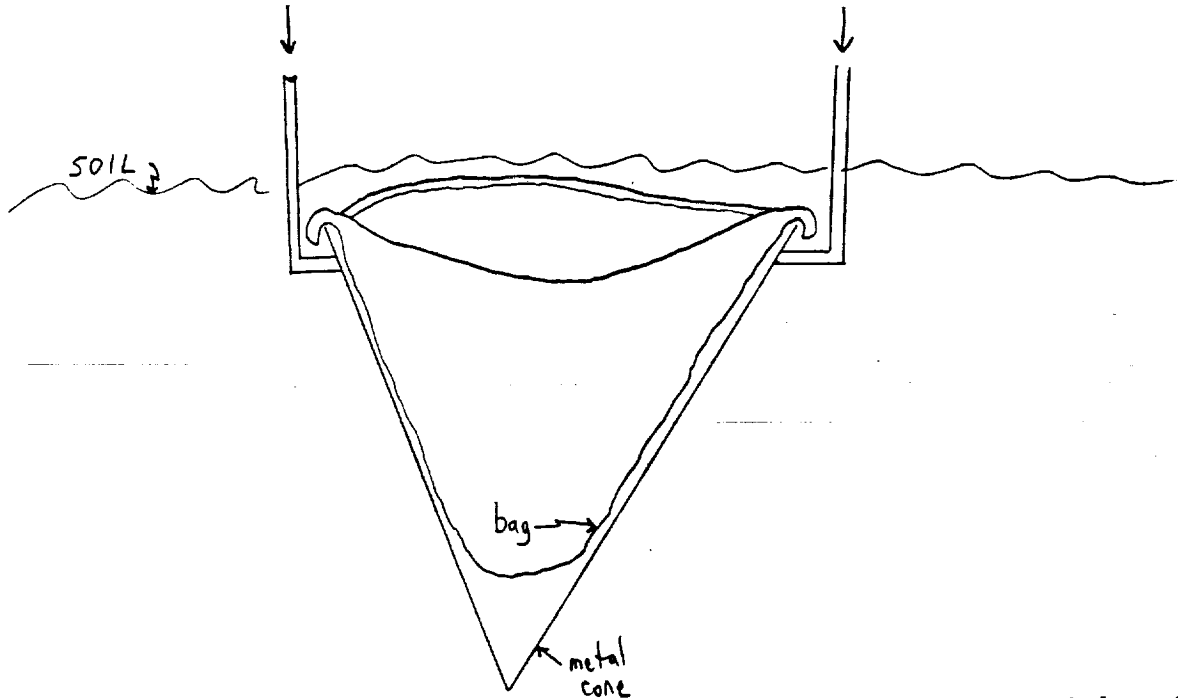

FIGURE 10(a)

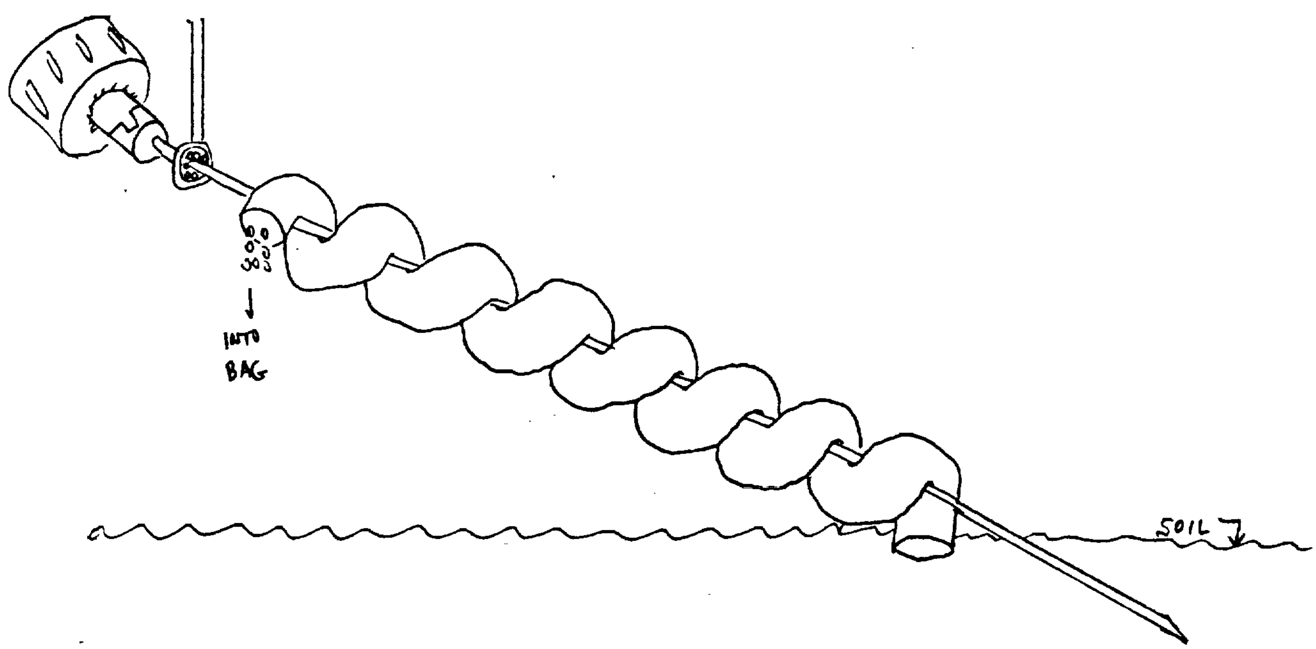

FIGURE 10(b)

which would vary with each location attempted because the subsurface density is not uniform. The repeated forced entry into the moon's surface leads to a great potential for cone-tip breakage and subsequent catastrophic breakdown of the entire machine. In avoiding this problem, the cone could be made short enough that it will penetrate only the soft uppermost layer of regolith, but then it is limited to small, non-ideally sized containers. Because of this unavoidable problem with the embedded cone, this design option was discarded.

The screw design, shown in Figure 10(b), utilizes the force of gravity to gradually move lunar dirt up a twisting ramp. The dirt is introduced through an opening in the tip, and as the screw slowly revolves, the dirt falls to its lowest level. The axis angle of the screw with the moon's surface ensures that the dirt raises one level with each revolution of the screw. Further investigation of the regolith's characteristics, however, revealed a large percentage of extremely fine textured dirt similar to talcum powder. This textured material resists "flowing", the basis of the entire screw design. Although the screw design would work well to lift slick objects or liquids, it would not work well on lunar regolith, for bridging might occur, and the design was rejected on that basis.

The shrouded paddle wheel design, sketched in Figure 11, lifts the regolith into a trajectory, which is controlled by a overhead shroud and

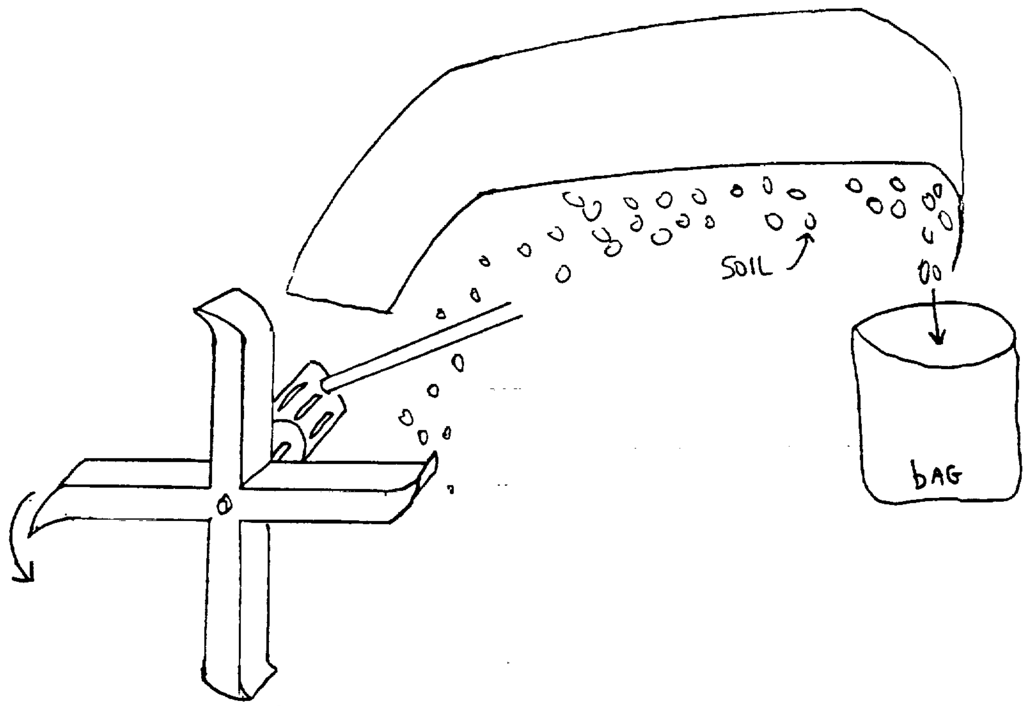

FIGURE 11

guided into a vertically placed bag. When the bag is full, it drops and closes with a drawstring mechanism woven into the lip of the bag similar to the way the forced ramp's container was closed. This design employs a good closure system and could be easily controlled electronically, but it is designed to create a very large ambient cloud of airborne regolith. If the paddle wheel is turning at a substantial speed most of the dust will be directed by the shroud into the waiting bag. However, a significant amount of the finely textured material will be floating in the vicinity of the gears, motors, and other moving mechanical parts, resulting in the greatest possibility of regolith-induced clogging among any of the designs discussed previously. For this reason, the paddle wheel/shroud design was discarded.

The "french fry scoop", shown in Figure 12, uses the inertia of the lunar dust in a similar manner as the forced ramp. The scoop is designed for attachment on a lunar truck and can move both in a vertical motion and in a horizontal motion under the truck using a motor system. After inserting the tip of the scoop into the first in a series of dixie cup stacked bags, an electric magnet in scoop is activated, attracting metallic threads woven into the folded lip of the bag and securing the bag onto the scoop. The scoop and bag are lowered to ground level and dragged along approximately two inches beneath the actual regolith surface. The scoop

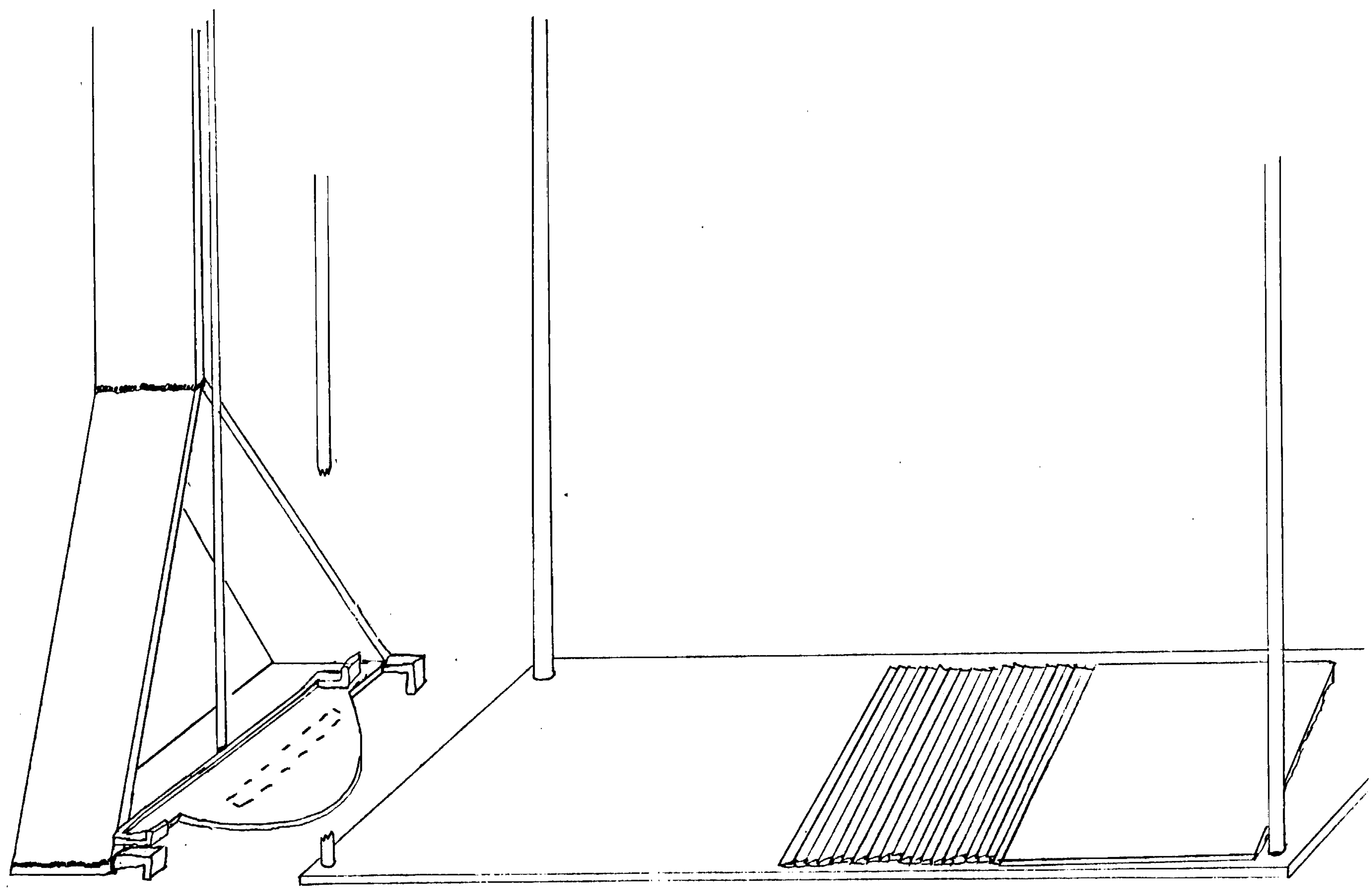

FIGURE 12 : LUNAR REGOLITH BAGGING SYSTEM

and bag sweep underneath the dirt until a weight sensor in the platform under the bag indicates it is nearly full. When the scoop rises, it tilts the rest of its dirt into the bag, filling it to capacity. As the scoop is removed, it draws an inner-folded lip outward, displacing a small amount of dirt and revealing magnets attached to the bag which are used to close the bag. The bag is dropped and the process is repeated until the dixie cup bundle is exhausted.

The "french fry scoop" disrupts the dirt only marginally, and thus minimizes the airborne dust. Also, most moving parts (the motors, horizontal track, etc.) are removed from the surface of the moon and contact with ambient dirt created would be very little. The control system is excellent, and the sealing mechanism utilizing magnets is valid for the temperature range specified and in operation in a vacuum environment. The scoop was chosen for further development as the bag-filling system.

BAG DESIGN DESCRIPTION

The bag design for the lunar regolith bagging system incorporates a working design of a bag capable of withstanding the radiation (electron and UV) environment, temperature range, and impact of small meteorites experienced on the surface of the moon while holding regolith in place for a service life of ten years.

The regolith bag was designed to be in the shape of a pillowcase. This shape offered a maximum regolith packing probability, a maximum regolith volume per fabric weight and a simplicity of design which lead to a minimum number of construction seams and potential weak areas. The criteria for the decision of the bag shape were discussed in detail previously.

The regolith bag is designed to have a width of three feet and a length of eighty-six inches, and to be fabricated from six ounces per square yard DuPont Kevlar 149 fabric in a rip-stop weave configuration. Kevlar will not degrade under constant ultraviolet exposure in the absence of oxygen and is transparent to electron (Beta) radiation. It is able to withstand temperatures from -300 to 800 degrees Fahrenheit and will not melt or become brittle. Kevlar 149 is cut and puncture resistant and it is light weight due to its low density.

Kevlar 149 was chosen over Kevlar 29, 49, and 129 because it is commonly used in apparel applications in the protective garment industry such as gloves, chaps, and vests. In these applications, high strength, toughness, and low linear density (lightweight) fabrics are necessary. For this project, these same characteristics are necessary in order to have a durable, strong fabric which will not be expensive to transport since weight is a major cost factor in space transportation.

The best seam to use, according to Mr. Roy Peek of Clark-Schwebel Fiberglass Corporation, for construction of the bags is a double-stitched, flat-felled seam. A flat-felled seam is one in which the fabric edges are wrapped around each other into interlocking "J's" and sewn together with double seams. Using this method, there are no open, raw edges. The recommended stitch density is seven to twelve stitches per inch. (Tent Book, p. 30)

The four 8.75 inch long rectangular magnets are sewn .25 inches apart into the upper edge of the bag, then folded down to form an inner "lip". Each of the magnets are fabricated with two holes in the center, then are sewn to the bag with Kevlar thread like buttons. (See Appendix F for specific magnetic calculations.) Each magnet contains approximately 17.25 cubic inches of a steel alloy made up of 6% tungsten, 0.7 % carbon, and 93.3% iron (Appendix F). Figure 13 shows the dimensions of the bag.

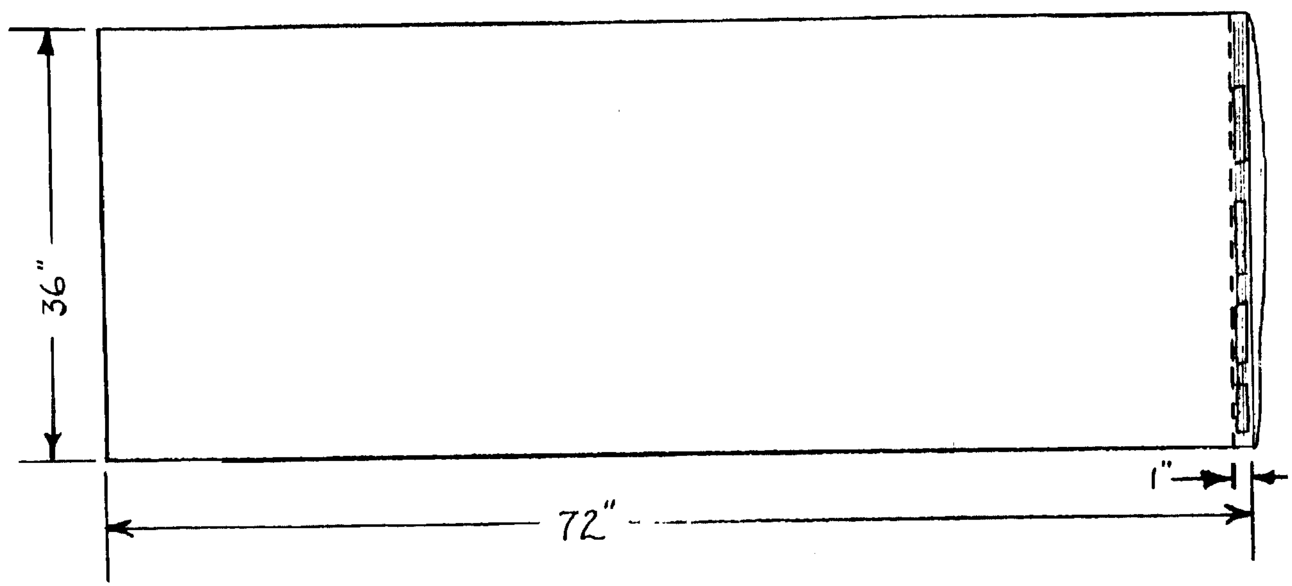

FIGURE 13 : LUNAR REGOLITH BAG

MECHANICAL DESIGN DESCRIPTION

The final design of the french fry scoop bag filling mechanism can best be described by discussing its setups and actions to accomplish its various tasks. It is modelled after the utensil used in fast food restaurants. Figures 14 and 15 reveal the dimensions of the three main parts of the design.

The entire scoop structure is attached to a lunar truck, as shown in Figure 12, which is moving at approximately seven kilometers per hour (towards the left side of the paper). Eighty bags rest in a "dixie cup" configuration with each bag inserted into the bag behind it. The bundle rests on a stationary platform near the rear of the truck with the opening facing forward. This platform extends one bag length to the front of the bundle. The scoop is attached to the truck by an arm which can move up and down, left and right, and forward and backward along an enclosed track. On the horizontal portion of the scoop are two hooks aimed downward. Beside the scoop is a rod that has two hooks aimed upward. The two hooks on the rod lie directly above the other two. All motions are controlled by an electronic microprocessor.

To open and attach the first bag in the dixie cup bundle, the scoop moves to a position directly in front of the bundle. Initially, the hooks are pressed flat together and the rounded portion of the scoop is inserted into

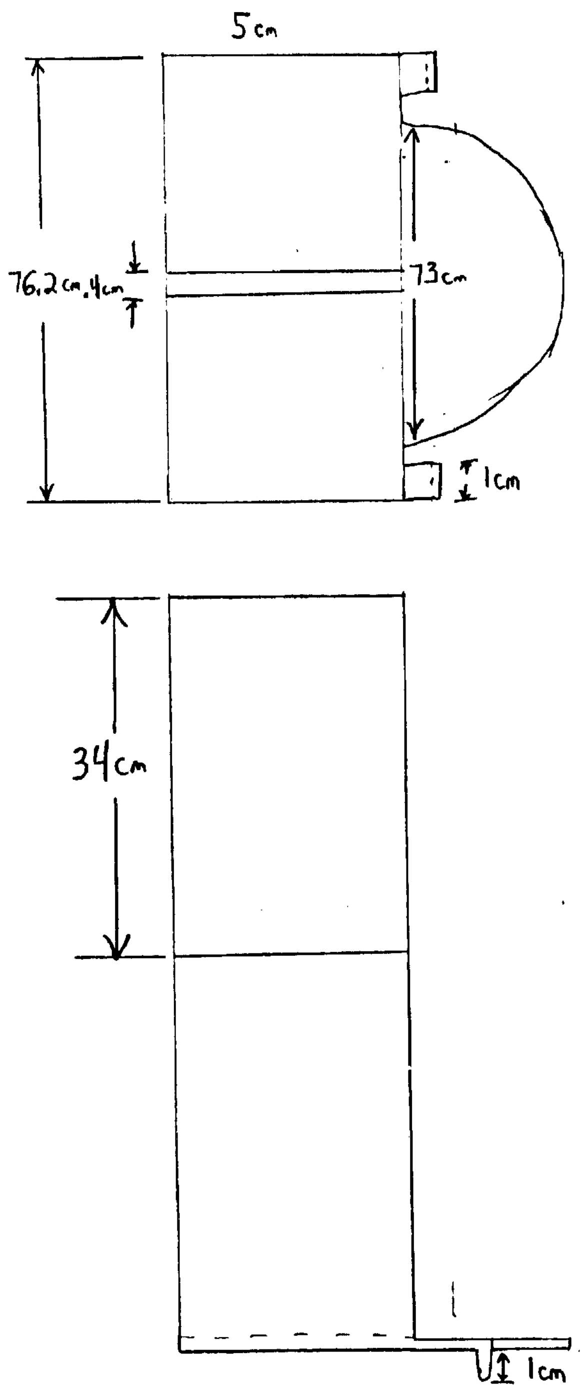

FIGURE 14.
DIMENSIONS NOT TO SCALE

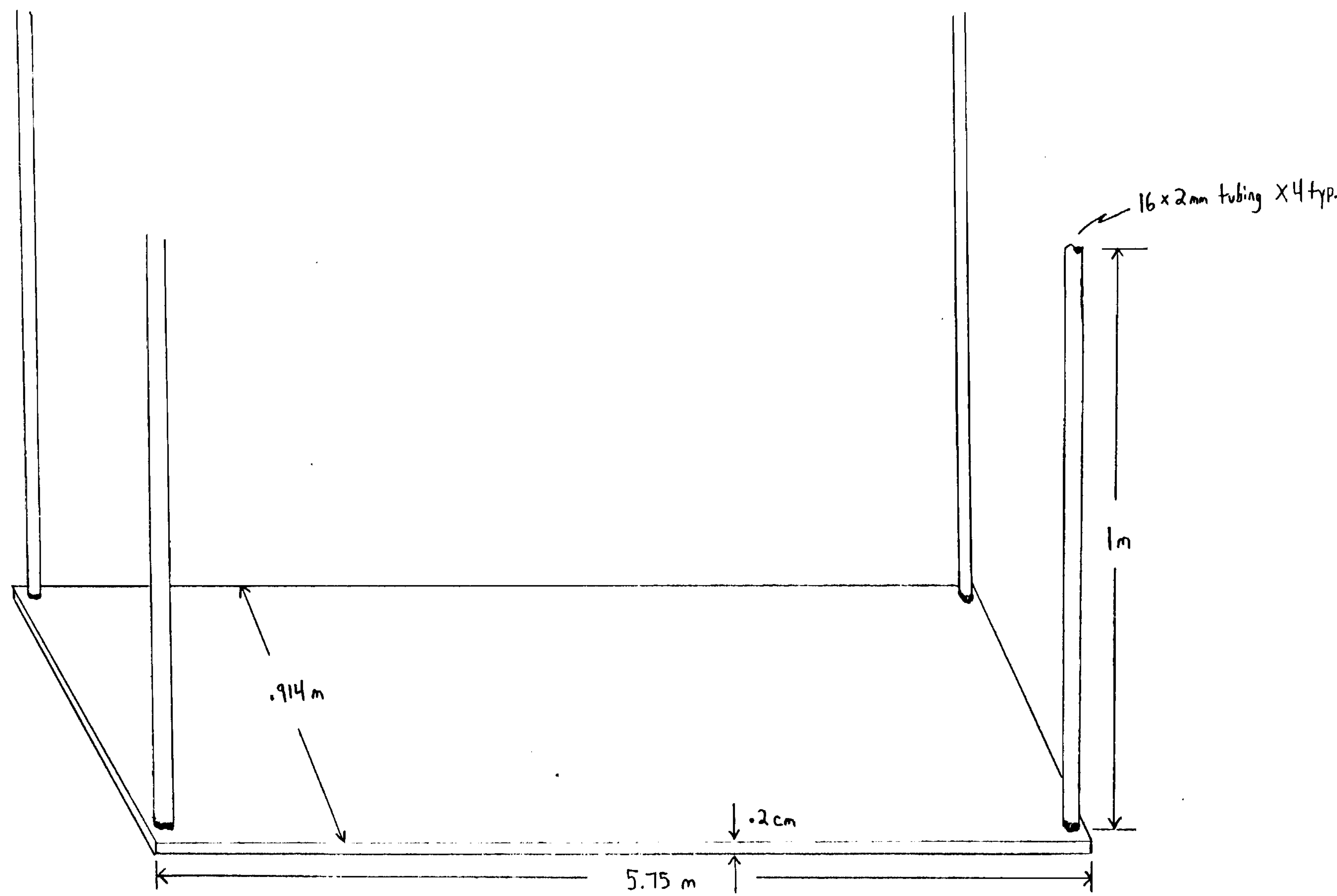

FIGURE 15
PLATFORM
MATERIAL : Al 6061 T-6

the bag opening. The electromagnet activates and the scoop withdraws the bag from the rest of the bundle. The four rods are then spread to a rectangular shape, holding the bag open for the incoming of the soil. When the scoop moves into the filling position on the ground, the horizontal force acting on the bag is negligible because the scoop and protective platform move together with the lunar truck. When actually in the filling position, the bag is resting on the stationary protective platform during the entire filling process.

Filling the bag relies heavily on the movement of the lunar truck. As the vehicle is moving, it will be gradually pushed three centimeters into the soil. The vehicle will move forward and the dirt, which follows the laws of inertia, will flow towards the rear of the bag. Meanwhile, the increasing weight of the dirt in the bag is being monitored closely by the electronic weight sensors in the filling platform which will eventually activate the closure system.

Without withdrawing the scoop from the filled bag, the scoop raises slightly, thus creating a ramp for the dirt contained in the scoop down into the upper portion of the bag. Then, simultaneously the four hooks, which have been holding the bag open all this time, withdraw, scraping against the outer edge of the bag and catching on the inner lip. The hooks draw the lip outward, displacing a small amount of the lunar dirt and revealing

the permanent magnets attached to the bag. The upper fold of the bag will fall at approximately 1.6 m/s^2. As the magnets on the edges of the bag come into proximity of each other the magnetic field surrounding them pulls the two halves of the bag together and the bag snaps shut. (See Appendix F for calculations).

The filled bag is now in the way of the scoop's journey to pick up another bag. However, by moving the scoop to the right side of the closed bag, the bag is pushed towards the left, off of the protective weight sensor platform and onto the dirt, without having to fall any distance that might cause it to burst open. The scoop then moves into position to pick up another bag, and the process begins again.

In keeping with the objective to minimize weight without sacrificing strength of material, the french fry scoop and all associated parts are to be constructed of Aluminum 6061-T6. All motors and microprocessors are to be constructed to maintain usability in the extreme temperature range (-250 F to +250 F) encountered on the moon's surface and must be able to radiate heat away from moving parts.

Assuming the lunar vehicle is moving at approximately seven kilometers per hour, the time to fill each bag should be only twelve seconds. Allowing six minutes for movement of scoop along the track and positioning the scoop and bag for filling, this design should be able to fill

and drop ten bags per hour, and all of the bags in twelve days. (Supporting calculations are included in Appendix H).

CONCLUSIONS:

Our simple design will bag lunar soil in a relatively short amount of time, with a low equipment weight, and with moving parts distanced from the dirt. The bags are made out of Kevlar 149 with a fabric weight of 6 oz. per square yard. All machine parts are composed of aluminum 6061-T6. Assuming that the vehicle runs at 7 km/hr for 8 hours a day, the machine will bag the necessary 450 m^3 of soil in about 12 days. The total mass of the bags and the machine to be shipped to the moon will be 687 kg. The cost of shipping this weight will be \$6.23 million.

RECOMMENDATIONS:

When the last few bags on the platform are to be filled, the scoop must attach itself to one bag without disrupting the others. To make sure that the action happens correctly, the last bag on the platform should be attached somehow to the platform. Heat-resistant Velcro is recommended.

The motors which are to control the motions of the scoop should withstand the large temperature range, expel heat by a radiative source, and not consume more than ten kilowatts of power. An 8-bit microprocessor is suggested to control the actions. A stretch of the Kevlar is recommended to cover these moving components and protect them from ambient dust.

A team should determine how to transport the bundles of bags to the vehicle.

The four magnets that are to be used in each bag should be sewn into the lip like buttons. They will need to be drilled first.

The scoop needs to be welded in many places. Tee welds by gas Tungsten-arc welding is recommended (Marks' 13-46).

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APPENDIX A

Cut Resistance Tests

APPENDIX A
CUT RESISTANCE TESTS

Tests to determine the resistance to cuts caused by a razor-sharp edge were conducted on several of high performance fabric samples in the physical testing laboratory in the School of Textile and Fiber Engineering at Georgia Tech.

Sample swatches of Kevlar (4.5 oz/sq yd and 6 oz/sq yd), 50/50 PBI/p-aramid blend (4.5 oz/ sq yd and 6 oz/sq yd), PBI (9.2 oz/sq yd), Teflon TFE (unknown oz/sq yd), and Nextel 312 (unknown oz/sq yd) were subjected to five passes in each the warp and the weft directions with a razor blade mounted in a utility knife frame ("warp" designates the warp yarns cut, whereas "weft" designates the weft yarns cut). Medium force was exerted by the operator on the razor knife in the first test. Heavy force was exerted by the operator on the razor knife in the second test. Ratings of "pass" or "fail" were given to the cut resistance of the samples after each test.

The results of the testing are shown below:

TABLE A.1: RESULTS OF MEDIUM FORCE CUT RESISTANCE

Fabric Sample	Summary of Warp Cut Resistance	Summary of Weft Cut Resistance
Kevlar (4.5)	pass (5/5)	fail (4/5)
Kevlar (6.0)	pass (5/5)	pass(5/5)
PBI/aram(4.5)	pass (5/5)	pass(5/5)
PBI/aram(6.0)	pass (5/5)	pass(5/5)
PBI (9.2)	pass (5/5)	pass(4/5)
Teflon TFE	fail (5/5)	fail (5/5)
Nextel 312	fail (4/5)	fail (5/5)

TABLE A.2: RESULTS OF HEAVY FORCE CUT RESISTANCE

Fabric Sample	Summary of Warp Cut Resistance	Summary of Weft Cut Resistance
Kevlar (4.5)	pass(5/5)	fail (3/5)
Kevlar (6.0)	pass(5/5)	pass(5/5)
PBI/aram(4.5)	pass(5/5)	pass(4/5)
PBI/aram(6.0)	pass(5/5)	pass(5/5)
PBI (9.2)	pass(4/5)	fail (4/5)

note: Teflon TFE and Nextel 312 not tested due to failure under medium force

APPENDIX B

Electron (β) and UV Radiation Resistance of DuPont Kevlar

R-1480E

DU PONT

ESTABLISHED 1802

E. I. DU PONT DE NEMOURS & COMPANY

INCORPORATED

P.O. Box 80701

WILMINGTON, DELAWARE 19880-0701

FIBERS DEPARTMENT

CHESTNUT RUN PLAZA

Fibers & Composites Development Centers
Oak Run, Chestnut Run Plaza
Wilmington, DE 19880-0701

February 22, 1990

Ms. Sabrina Brown
Georgia Tech.
P.O. Box 35405
Atlanta, GA 30332

Dear Ms. Brown:

Enclosed are a number of technical papers and data sheets dealing with UV and other radiation resistance properties of Kevlar® aramid fibers and their composites. It is important for you to distinguish between degradation under radiation exposure and transmission or shielding properties. Unless protected, Kevlar® will degrade under constant UV exposure (less in absence of oxygen), but it is strongly absorbing. Kevlar® has good electron and gamma radiation resistance, but it will transmit them, especially gamma.

Good luck in your NASA project.

Sincerely,

INDUSTRIAL APPLICATIONS RESEARCH

Paul G. Riewald

Paul G. Riewald
Sr. Research Associate

PGR:sm
Enc.

THE EFFECT OF ULTRAVIOLET LIGHT ON PRODUCTS BASED ON FIBERS OF KEVLAR® 29 AND KEVLAR® 49 ARAMID

AUGUST 1977

interior fibers are shielded by the strong absorption of the surface fibers. UV stability therefore increases with the size of the fiber array, increasing with yarn denier or with diameter, as in ropes and cables (Table I). In some cases, the small strength loss associated with UV degradation in large diameter ropes and cables is acceptable and no further protection is required. Where this is not the case, two techniques are available -- overbraiding and jacketing (Table II).

In overbraiding, the entire cable or individual sub-elements are wrapped with a light-stable fiber such as Dacron® polyester, providing a UV shield. Added weight of the order of 20% on a two-inch diameter cable weighing two lb/ft is typical. In jacketing, a continuous sheath of opaque polymer, usually black urethane, is extruded onto the cable or sub-elements giving add-ons of 15% on 0.9 lb/ft cable. Impregnation of individual strands--for example, urethane--as required for cabling operations, is by itself generally not sufficient for UV protection and an additional jacket is recommended.

FABRICS, TAPES AND WEBBINGS

UV protection is especially critical for woven fabrics and some tapes and webbings of Kevlar® aramid where the thickness of the fiber array is insufficient for effective self-shielding. The best protection is offered by pigmented resin coating or film lamination (Table III). In some cases, overbraiding with light stable fiber is possible. Where coating or film is used, pigmentation which is visually transparent should be avoided since many so-called UV absorbers and screeners do not cover the entire region between 300 and 450 nm where Kevlar® is sensitive. The most effective screen is opaque, but some translucence is acceptable providing only non-damaging light is admitted.

BALLISTIC AND PROTECTIVE GARMENTS

Most garments based on Kevlar® aramid will be protected from the effects of UV either by a fabric jacket or by a resin coating. Thus, home laundering and drying in the sun of a jacketed ballistic garment should not result in loss of protection due to UV degradation. Unprotected garments, or those from which the protective covering has been removed, should not be exposed to sunlight to avoid possible deleterious effects.

• Fiber reinforced composites based on Kevlar® normally do not require special UV protection. If protection is desired, apply a pigmented gel or surface coat.

• Determine the validity and acceleration factor of accelerated UV exposure tests for the material and system of interest before using test data for design.

MWW:LHM/kb
August 11, 1977

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FIGURE 2

OVERLAP OF ABSORPTION OF KEVLAR® WITH SOLAR SPECTRUM

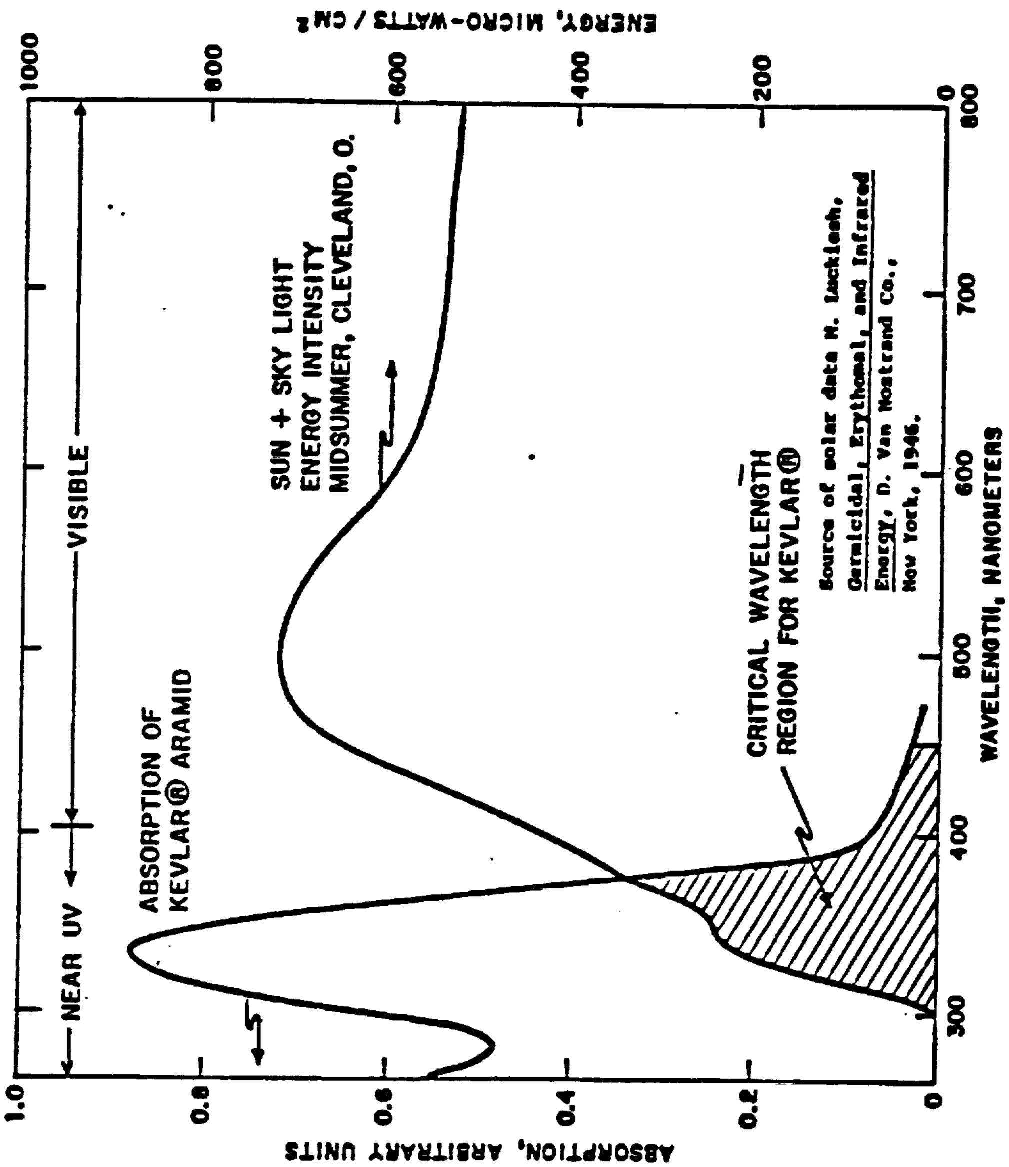

TABLE II

UV PROTECTION OF ROPES AND CABLES

	% Tensile Strength Lost
Braided Rope, Kevlar® 29 Aramid 1000 hrs "Weather-Ometer"	
Bare (1/4")	43
Same with Dacron® T-68 Polyester Overbraid (5/16")	6
Stranded Cable, Urethane Impregnated Kevlar® 49 Aramid 7x7 500 hrs "Weather-Ometer"	
Bare (1/4")	16
Same with 20 mil Black Urethane Jacket	<2

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TABLE IV

EFFECT OF ULTRAVIOLET EXPOSURE ON THE TENSILE STRENGTH OF COMPOSITES REINFORCED WITH KEVLAR®149 AND FIBERGLASS FABRICS

CARBON ARC EXPOSURE

Exposure	Kevlar®149/ Epoxy (a)	Kevlar®149/ Polyester (b)	"E"-Glass/ Polyester (c)
None	67,900 (d)	43,700	37,000
No UV 120°F, 93% R.H. 1584 hr	70,000	41,700	31,600
Weatherometer 500 hr	63,800	46,800	30,700
Weatherometer 1000 hr	76,000	33,600	34,900
Fadeometer 870 hr	68,500	38,300	31,100
Weatherometer 100 hr + 72 hr Salt Water Soak + 600 hr Fadeometer	68,600	37,300	31,700

(a) 2 Plies Style 181 + 1 ply Style 120/Hexcel "F-155"; 55 vol. %.
(b) 2 Plies Style 281 + 1 ply Style 120/Mahogany "Dion 6908"; 40 vol. %.
(c) 2 Plies Style 181 + 1 ply Style 120/Mahogany "Dion 6908"; 40 vol. %.
(d) Each value an average in lb/in^2 of 3 axial tensile breaks.

APPENDIX C

Bag Shape Calculations

APPENDIX C
BAG SHAPE CALCULATIONS

The regolith-filled volume of the pillowcase shape approximates the volume of a cylinder, which is given by:

$$V_{cylinder} = \pi\, r*r*h, \quad \text{where } r \text{ is found by:}$$

$$\text{circumference of a cylinder} = 2\pi r = 2(\text{width})$$

$$\text{therefore, } r = \frac{\text{width}}{\pi}, \quad \text{and } h = \text{length}$$

$$V_{regolith} = \frac{\text{width*width*length}}{\pi}$$

The Regolith Packing Potential of the pillowcase shape is given by:

$$\frac{\text{Regolith Volume}}{\text{free volume}} = \frac{\text{width*width*length}}{\pi}$$

The regolith volume of the bread bag approximates the volume of a cylinder, minus two small triangular volumes at the base corners.

$$V_{cylinder} - 2V_{triangular} = \frac{\text{width*width*length}}{\pi} - \frac{2(\text{base area*height})}{3}$$

The triangular volume will vary according to the height of the tacking stitch along the side of the bag.

The regolith volume of the bread bag is maximized when the triangular volumes are equal to zero, or in other words, when the bread bag does not have any tacking stitches -- which then makes it a pillowcase.

From these calculations, it can be found that the regolith packing potential is greater for the pillowcase shape than for the bread bag shape.

APPENDIX D

Bag Size Idealization

APPENDIX D
BAG SIZE IDEALIZATION

The pillowcase shape was used to idealize the size of the regolith bag. The volume of the bag fabric is directly proportional to the surface area of the fabric for a constant fabric thickness.

The surface area is found by:

$$A_{sur} = 2*width*length,$$

so,

$$V_{fabric} = 2*width*length*thickness$$

The equation for the volume of regolith was found in Appendix C as:

$$V_{regolith} = \frac{width*width*length}{\pi}$$

Taking the first derivative with respect to length of both the fabric volume and the regolith volume equations gives:

$$\frac{dV_{fabric}}{dl} = 2*width*thickness = (constant)*width$$

$$\frac{dV_{regolith}}{dl} = \frac{width*width}{\pi}$$

This shows that the equations depend upon the width for change, and so a constant length may be assumed for purposes of width idealization.

The surface area is directly proportional to the fabric volume, and so if a constant thickness is assumed to be equal to one inch, the surface area may be used to calculate the fabric volume. To do this, a length equal to ten inches is used. The idealized width was calculated from a range of widths from 6 to 60 inches.

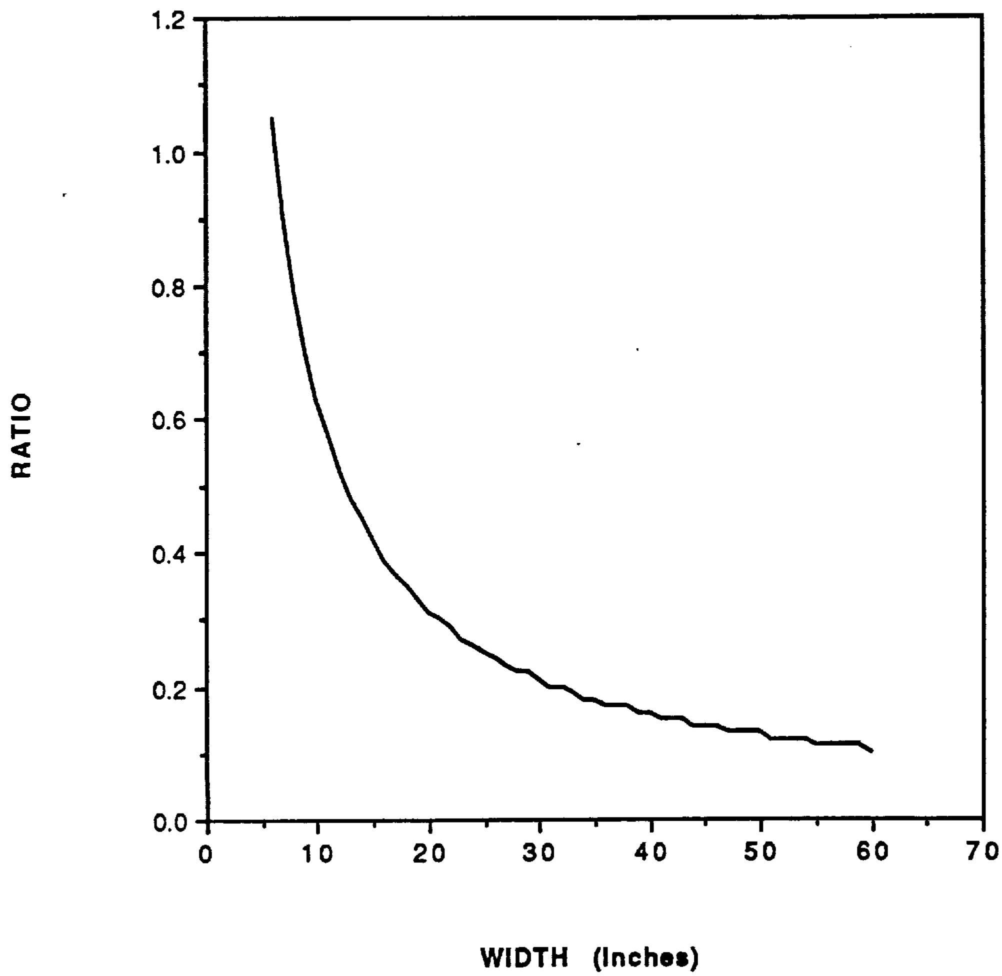
A graph of surface area versus regolith volume was generated, and from this graph, an exponential increase in the regolith volume can be seen as the surface area increases.

A ratio of the surface area to regolith volume was then calculated for the range of widths. A graph of the widths versus the ratio of surface area to regolith volume was made. From this graph, an exponential decrease in the ratio occurs, and begins to level off above 30 inches. At the levelled off portion of the curve less change in the ratio of surface area to regolith volume occurs. A width of 36 inches was chosen from this idealized section of the curve. The 36 inch width was chosen because it is about the maximum commercially available width for a doubled over fabric (total fabric width of 72 inches). And it is possible to obtain Kevlar in 72 inch fabric widths.

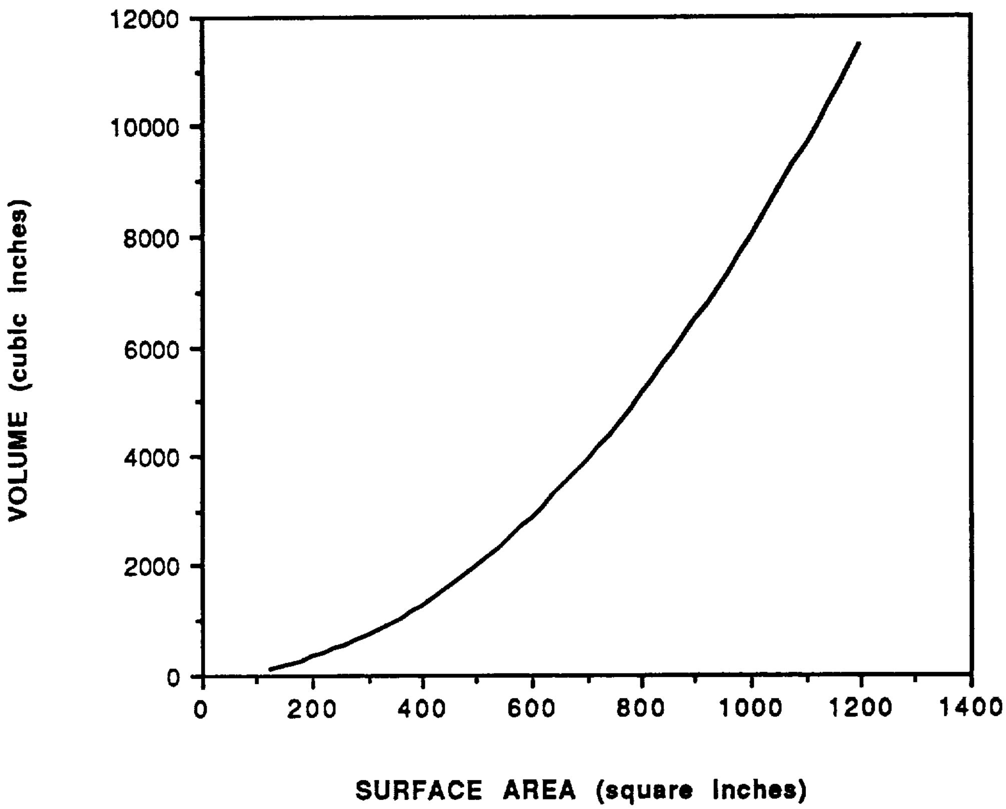
The data and graphs follow:

	WIDTH	SURFACE AREA	VOLUME	RATIO
1	6	120	115	1.05
2	7	140	156	0.90
3	8	160	204	0.79
4	9	180	258	0.70
5	10	200	318	0.63
6	11	220	385	0.57
7	12	240	458	0.52
8	13	260	538	0.48
9	14	280	624	0.45
10	15	300	716	0.42
11	16	320	815	0.39
12	17	340	920	0.37
13	18	360	1031	0.35
14	19	380	1149	0.33
15	20	400	1273	0.31
16	21	420	1404	0.30
17	22	440	1541	0.29
18	23	460	1684	0.27
19	24	480	1833	0.26
20	25	500	1989	0.25
21	26	520	2152	0.24
22	27	540	2320	0.23
23	28	560	2496	0.22
24	29	580	2677	0.22
25	30	600	2865	0.21
26	31	620	3059	0.20
27	32	640	3259	0.20
28	33	660	3466	0.19
29	34	680	3680	0.18
30	35	700	3899	0.18
31	36	720	4125	0.17
32	37	740	4358	0.17
33	38	760	4596	0.17
34	39	780	4841	0.16
35	40	800	5093	0.16
36	41	820	5351	0.15
37	42	840	5615	0.15
38	43	860	5886	0.15
39	44	880	6162	0.14
40	45	900	6446	0.14
41	46	920	6735	0.14
42	47	940	7031	0.13
43	48	960	7334	0.13
44	49	980	7643	0.13
45	50	1000	7958	0.13
46	51	1020	8279	0.12
47	52	1040	8607	0.12
48	53	1060	8941	0.12
49	54	1080	9282	0.12
50	55	1100	9629	0.11
51	56	1120	9982	0.11
52	57	1140	10342	0.11
53	58	1160	10708	0.11
54	59	1180	11080	0.11
55	60	1200	11459	0.10

RATIO OF BAG MATERIAL VOLUME TO REGOLITH VOLUME for LENGTH=10"



BAG SURFACE AREA VS. REGOLITH VOLUME
for Length=10



for baglength=72 inch

width in inches	volume of bag fabric (cu inch)	volume of regolith (cu inch)	ratio: fabric volume to regolith volume	mass of bag fabric (lb/bag)	mass of regolith (lb/bag vol)	total mass regolith + fabric (lb-mass)	ratio: fabric mass to regolith mass
6	5	825	.005938	0.25	36	36.02	.006985
7	6	1123	.005089	0.29	49	48.97	.005988
8	7	1467	.004453	0.33	64	63.92	.005239
9	7	1856	.003958	0.37	80	80.85	.004657
10	8	2292	.003563	0.42	99	99.77	.004191
11	9	2773	.003239	0.46	120	120.67	.003810
12	10	3300	.002969	0.50	143	143.56	.003493
13	11	3873	.002740	0.54	168	168.44	.003224
14	11	4492	.002545	0.58	195	195.31	.002994
15	12	5157	.002375	0.62	224	224.16	.002794
16	13	5867	.002227	0.67	254	255.00	.002620
17	14	6623	.002096	0.71	287	287.83	.002465
18	15	7426	.001979	0.75	322	322.65	.002328
19	16	8273	.001875	0.79	359	359.45	.002206
20	16	9167	.001781	0.83	397	398.24	.002096
21	17	10107	.001696	0.87	438	439.01	.001996
22	18	11092	.001619	0.92	481	481.77	.001905
23	19	12124	.001549	0.96	526	526.52	.001822
24	20	13201	.001484	1.00	572	573.26	.001746
25	20	14324	.001425	1.04	621	621.98	.001677
26	21	15493	.001370	1.08	672	672.69	.001612
27	22	16707	.001319	1.12	724	725.39	.001552
28	23	17968	.001272	1.17	779	780.08	.001497
29	24	19274	.001228	1.21	836	836.75	.001445
30	24	20626	.001188	1.25	894	895.41	.001397
31	25	22024	.001149	1.29	955	956.05	.001352
32	26	23468	.001113	1.33	1017	1018.68	.001310
33	27	24958	.001080	1.37	1082	1083.30	.001270

34	28	26494	.001048	1.42	1148	1149.91	.001233
35	29	28075	.001018	1.46	1217	1218.50	.001198
36	**29**	**29702**	**.000990**	**1.50**	**1288**	**1289.08**	**.001164**
37	30	31375	.000963	1.54	1360	1361.65	.001133
38	31	33094	.000938	1.58	1435	1436.21	.001103
39	32	34859	.000913	1.62	1511	1512.75	.001075
40	33	36669	.000891	1.67	1590	1591.28	.001048
41	33	38526	.000869	1.71	1670	1671.79	.001022
42	34	40428	.000848	1.75	1753	1754.29	.000998
43	35	42376	.000829	1.79	1837	1838.78	.000975
44	36	44370	.000810	1.83	1923	1925.26	.000953
45	37	46409	.000792	1.87	2012	2013.72	.000931
46	38	48495	.000774	1.92	2102	2104.18	.000911
47	38	50626	.000758	1.96	2195	2196.61	.000892
48	39	52804	.000742	2.00	2289	2291.04	.000873
49	40	55027	.000727	2.04	2385	2387.45	.000855
50	41	57296	.000713	2.08	2484	2485.85	.000838
51	42	59610	.000699	2.12	2584	2586.23	.000822
52	42	61971	.000685	2.17	2686	2688.61	.000806
53	43	64377	.000672	2.21	2791	2792.97	.000791
54	44	66830	.000660	2.25	2897	2899.31	.000776
55	45	69328	.000648	2.29	3005	3007.65	.000762
56	46	71872	.000636	2.33	3116	3117.97	.000748
57	47	74461	.000625	2.37	3228	3230.28	.000735
58	47	77097	.000614	2.42	3342	3344.57	.000723
59	48	79778	.000604	2.46	3458	3460.85	.000710
60	49	82506	.000594	2.50	3577	3579.12	.000699

The thickness of the fabric was found as follows:

$$\frac{(6.0 \text{ oz/sq yd})*(1\text{yd}) \quad *(1 \text{ lb})}{(36 \text{ in}) \quad *(16 \text{ ounces})} = .000289 \text{ lb/sq in}$$

The density of Kevlar 149 = 1.45 gm/cc = .051 lb/cu in

$$\text{thickness} = \frac{\text{mass/area}}{\text{mass/volume}} = \frac{.00028 \text{ lb/sq in}}{.051 \text{ lb/cu in}}$$

$$\text{thickness} = .00567 \text{ inches} = 5.67 \text{ mils}$$

To further demonstrate the idealization, the volume of the bag fabric was calculated using a range of widths again from 6 to 60 inches, the specified length of 72 inches, and a fabric thickness of 5.67 mils.

A ratio of the fabric volume to the regolith volume was calculated. The mass of the bag fabric was calculated from the fabric volume and the density of the fabric (.051 lb/cu in).

$$\text{mass (lb)} = \text{volume (cu in)} \; * \; \text{density (lb/cu in)}$$

The mass of the regolith was calculated similarly from the regolith volume and the density of the regolith (1.2 g/cc = .04335 lb/cu in).

Ratios of regolith mass to fabric mass were calculated for the range of widths. The total filled mass of each bag for the range of widths was calculated by:

$$\text{Total mass of bag} = (\text{Regolith Mass} + \text{Fabric Mass})$$

The tensile strength of 6 ounce per square yard Kevlar 149 fabric is approximately 2760 MPa. After long exposure periods to high heat, at least 50% of its original strength will remain.

Calculations to determine if the strength of the fabric will be sufficient to support the weight of the regolith are as follows:

$$\text{Tensile stress} = \sigma = \text{Force/Area}$$

Force = (Vol of regolith)*(density of regolith)*(lunar gravity)

= (29702 cu in)*(.04335 lb/cu in)*(32/6ft/sq sec)*(12in/ft)

= 82406 lb*in/sq sec = 949.4 kg*m/sq sec

Force = 949.4 N

$$\text{Area}_{cs} = \frac{\text{width*width}}{\pi} = \frac{36*36}{\pi} = 11.46 \text{ sq in}$$

Area = .0074 sq meters

$$\sigma_{\text{regolith}} = \frac{949.4 \text{ N}}{.0074 \text{ sq m}} = 128{,}400 \text{ Pa} = .128 \text{ MPa}$$

$$\frac{\sigma_{\text{fabric}}}{\sigma_{\text{regolith}}} = \frac{1380 \text{ MPa}}{.128 \text{ MPa}} = \text{approx. } 10{,}000$$

The tensile stress caused by the weight of the regolith is negligible compared to the amount of tensile strength the fabric is able to withstand.

APPENDIX E

Bag Shape, Size and Fabric Alternatives and Decision Matrices

Material Alternatives Matrix

	A	B	C	D	E	F
1		Unaffect by B-Rad	Resist Vac UV Rad	Cut Resistant	Service Temps	Density
2	**ORGANIC FABRICS:**					
3	**Kevlar**	**Yes**	**Yes**	**Yes**	**within**	**1.54 g/cc**
4	Nomex	No	-	Yes	within	-
5	PBI/aramid blend	No	-	Yes	within	-
6	Teflon TFE	No	-	No	within	-
7	Spectra 900	Info not known	-	Yes	within	-
8						
9	**INORGANIC FABRICS:**					
10	Fiberglass	Yes	Yes	Not very	within	-
11	Nextel ceramic	Yes	Yes	No	within	-
12	metals	Yes	Yes	Yes	within	varies
13						
14						
15	**INORGANIC PAPER:**					
16	Nomex paper	No	-	Yes	within	-
17	Nextel paper	Yes	Yes	No	within	-
18						
19	**ORGANIC FILMS/RESINS:**					
20	Teflon FEP	No	-	No	within	-
21	Teflon PFA	No	-	No	within	-
22	Tefzel fluoropolymer	No	-	No	within	-

BAG SHAPES

PILLOWCASE -- UNCONSTRUCTED SHAPE LIKE A PILLOWCASE

GINGER'S PIE POCKET -- MADE BY PILING REGOLITH ONTO A (ROUND) BOTTOM LAYER, AND THEN COVERING WITH A TOP LAYER- LIKE AN APPLE PIE

CONE -- SHAPED LIKE A SUGAR ICE CREAM CONE - ROUND OPENING

ACCORDION PLEATED BAG -- ANY BAG SHAPE - TO BE USED WITH SOME CLOSING MECHANISMS

BREAD BAG -- CYLINDRICAL WITH A FLAT BOTTOM

GROCERY BAG -- SQUARE WITH A FLAT BOTTOM

TUBE SOCK -- SIMILAR TO BREAD BAG / PILLOW BUT LONGER & NARROWER

SHOE BOX -- BOX WITH A REMOVABLE LID

SQUARE PILLOW -- A CONSTRUCTED SHAPE WITH EDGES AND CORNERS AND AN OPENING ON ONE EDGE OR SIDE

PYRAMID BAG -- IN THE SHAPE OF A PYRAMID WITH A FLAT BOTTOM AND SIDES SLOPING IN SO THAT THE OPENING IS NARROWER AT THE TOP

	A	B	C	D	E	F
1		Regolith Packing Potential	Simplicity:	Applicable	Storage	Fabric Structure
2	BAG SHAPE:	Max Reg Vol/ Fabric Vol	#Seams Req'd	to Design	Method	Limitations
3						
4	**Pillowcase**	**Good**	**Yes**	**Yes**	**any**	**No**
5	Pie Pocket	Poor	Yes	No	flat	No
6	Cone	Poor	Yes	Yes	flat/dixie	No
7	Accordion Pleated Ba	Good	Yes/No	Yes	special	No
8	Bread Bag	Good	Yes	Yes	any	No
9	Grocery Bag (square)	Good to Fair	No	No	fold/flat	No
10	Tube sock	Good	Yes	Yes	any	Yes - Knit only
11	Shoe box	Fair	No	No	special	No
12	Square Pillow	Goor to Fair	No	No	any	No
13	Pyramid Bag	Fair	No	No	flat	No

BAG STORAGE METHODS

COMPUTER PAPER STACKING:

a) ends connected
b) ends staggered or overlapped (Kleenex®)

GROCERY PRODUCE BAG / TOILET PAPER ROLL:

a) ends connected
b) ends staggered or overlapped

DIXIE CUPS:

a) horizontal
b) vertical

FLAT STACK

a) horizontal
b) vertical

VERTICALLY STACKED / CONNECTED:

bags stacked together vertically in groups of 10 or so, with the openings connected -- when opened, the entire group is opened, like multiple coin purses, at one time

Bag Storage Alternatives Matrix

	A	B	C	D	E	F	G
1		Applicable to	Ease of Bag	Degrees Freedom	Perm Deformation	Max # Bags	Need for Packing
2	**STACK/STORE OPTIONS:**	Regolith Machine	Withdrawal	Req'd to Load Bag	from Storage ?	per Bundle	Aids(container?)
3							
4	Computer Paper (connected	No	Low	High	Yes-folds	Good	Yes?
5	Kleenex (staggered)	No	Low	Medium	Yes-folds	Good	Yes
6	Toilet Paper (connected)	No	Low	Medium	No	Good	No
7	Roll (staggered)	Yes	High	Low	No	Good	No
8	**Dixie Cups -horizontal**	**Yes**	**High**	**Low**	**Yes?**	**Fair**	**No**
9	Dixie Cups - vertical	No	High	Medium	Yes?	Fair	Yes
10	Flat stack -horizontal	No	High	Low	No	Good	No?
11	Vertical stack	No	-	-	-	-	-
12	Vertically stacked/connect	No	-	-	-	-	-

APPENDIX F

Magnetic Calculations

APPENDIX F: MAGNETIC CALCULATIONS

The magnetic attraction between two materials can be described using Coulomb's Law:

$$\frac{m\ m'}{d^2} = \text{attractive force}$$

where m, m' represent the two pole strengths of the materials and d represents the separation distance.

Pole strength can be represented as a function of intensity of magnetization, J, and surface area of the magnet, A, as follows:

$$m = J * A.$$

J can be further defined in a relationship between permeability of the specific material used in the magnet, μ, and the impressed field intensity, H.

$$J = \frac{(\mu - 1)\ H}{4\pi}$$

It should be noted that permeability varies with each material used and also with temperature, showing a marked variance at the material's Curie point.

Inserting this definition of J into the original equation for pole strength, the following equation is derived:

$$m = \frac{(\mu - 1)}{4\pi} H * A\ .$$

At this point, the field intensity is the only parameter to be further defined, since the permeability is dependent on the material used and the area is controlled by the designer. Fortunately, the field intensity can also be controlled during the magnetization process on earth by identifying the following relationships.

The magneto-motive force, mmf, can be defined as

$$mmf = H\ pm$$

where pm is the mean path length of the magnetic force.

Alternatively, mmf can be proven to be the work done in carrying a unit magnetic pole once around the closed circuit, or

$$mmf = \frac{4\pi n\ I}{10} \quad ergs = 125.6637 \text{ x } 10(-6)\ n\ I \text{ Newtons}$$

where n is the number of windings and I is the current in the wire.

Equating the two expressions for mmf, the following expression is derived:

$$H\ pm = (125.6637 * 10(-6))\ \ n\ \ I$$

which yields the following expression for H in MKS units

$$H = \frac{125.6637\ *\ 10(-6)\ n\ I}{p\,m}\ .$$

Returning to the equation defining the pole strength,

$$m = \frac{(\mu\ -\ 1)\ (125.6637\ *\ 10(-6))\ n\ I\ A}{4\ \pi\ pm}$$

$$m = \frac{(\mu\ -\ 1)\ (10\ exp\text{-}6)\ n\ I\ A}{4\ \pi\ p\,m}\ .$$

As was noted earlier, permeability is specific to the material used in constructing the magnet and changes with extreme temperature fluxuations. Because of the relationship between permeability and the intensity of magnetization, J, the strength of the magnetization is also affected by extreme temperature fluxuations in the following manner.

For every ferromagnetic material, those materials that can be used to create a permanent magnet, there exists a temperature above which the magnetic properties fail completely and fairly suddenly. This temperature is called the Curie point and is a property of both the metallic alloy itself and the method of preparation. However, upon cooling the material below the Curie point, the crystal structure of the metal reallligns in such a way that the magnetic property of permeability is actually improved. This process is called magnetic annealing, and the cooling rates and temperatures should be carefully controlled to achieve desired results. (Magnetic Materials, p 80.)

The material specified in construction of the permanent magnets used in the french fry scoop design is a tungsten magnetic steel made up of approximately 6 % tungsten, 0.7 % carbon, and 93.3% iron. Extreme care should be taken during the fabrication of this alloy to minimize the introduction of impurities, as this would decrease the magnetic properties. This type of steel can maintain an energy level of greater than 1380 J/cubic meter (Applied Magnetism, p 46 with appropriate conversions from Marks'). A factor of safety of 1.5 results in a nominal value of 920 J/cubic meter to be used in calculations.

Since mmf for the magnet has already been determined to be

$$\text{mmf} = H\ \text{pm},$$

magnetic force intensity, H, for the magnet can be defined as

$$H = \frac{(920\ \text{J/cubic meter})}{\text{pm}}\ .$$

Assuming 4 magnets in a 36 inch circumference bag lip, allowing .25 inches between each magnet, each magnet's pm would be 8.75 inches, or 22.225 cm long. Therefore, the previous expression reduces to

$$H = \frac{920\ \text{J/cubic meter}}{.22225\ \text{m}}$$
$$= 4.1397\ \text{kJ/m\^{}4}$$

$$= 4.1397\ \text{kN/m\^{}3}$$ for each magnet in the 4 magnet system.

The critical factor in the magnet's closure potential is its ability to support the weight of the regolith without shearing. In its horizontal resting position, approximately half of the regolith in the filled bag exerts a pressure on the magnetic closure, according to Pascal's principle (Marks', p 3.38).

This pressure can be calculated to be

$$P = \rho\ g\ dz$$

where ρ is the density of the regolith, 1.2 g/cubic cm,
g is the acceleration of gravity on the moon, 1.6 m/s^2,
and dz is the depth of the regolith.

$$P = \frac{(.0012\ kg)}{10^{-6}\ m^3}(1.6\ m/s^2)(5.73\ in)(.0254\ m/in)$$

$$= [279.44\ N/m^2]\ [.5\ \pi\ r^2]$$

$$= 279.44\ (.133) = 37.16552\ N.$$

For each magnet in the 4 magnet system, this reduces to a pressure of

$$P = 9.29\ N.$$

For a shear force calculation, a frictional coefficient must be used; for dry steel to steel contact, the static friction coefficient is about 0.78 (Marks', p 3.25). Therefore the intensity strength can be represented as

$$H = 4139.7\ (C)\ (.78) = 3229\ (C)\ \text{Newtons},$$

using the variable (C) to represent the undetermined volume of each magnet. Forming a ratio of the intensity strength per volume and the necessary pressure, the following required magnetic volume can be determined:

$$H/P = \frac{3229\ (C)}{9.29}$$

$$(C) = \frac{9.29}{3229} = .00029\ \text{cubic meters.}$$

The following dimensions meet the volumetric requirements outlined above.

length = 22.225 cm = 8.75 inches

width = 10.0 cm = 3.94 inches

thickness = 1.295 cm = 0.5 inches

Using magnets of this size, the total mass of the 4 magnet system can be determined to be 9.21 kg. (Marks', p 6.44.)

APPENDIX G

Fastening Methods Decision Matrix

FASTENING MEANS

ZIPLOCK -- SELF SEALING LIKE A ZIPLOCK® BAGGIE

HEAT SEAL -- a) ADHESIVE ALREADY ON BAG
b) ADHESIVE IN MACHINE

TIE -- TIE HANDLES LIKE A TRASH BAG

DRAWSTRING -- PULL DRAWSTRING TO CLOSE BAG (LAUNDRY BAG)

COIN PURSE -- SELF EXPLANATORY (?)

SHRINK WRAP -- SHRINK BAG / PACKAGING OVER REGOLITH

BUCKLE -- a) BELT BUCKLE
b) SNAP BUCKLE (DOG COLLAR OR SEPARABLE KEY CHAIN)

SNAP -- SEE BLUE JEANS

BUTTONS -- SEE DRESS SHIRT

METAL DISC CRUSHED SHUT -- LIGHT WEIGHT, PLIABLE METAL OR OTHER MATERIAL THAT CAN BE CRUSHED SHUT WHEN BAG IS FULL

STITCH -- SEW BAG SHUT WITH APPLICABLE THREAD TYPE

PHIL'S NEWSPAPER BAG -- ONE BAG FITTED OVER ANOTHER FILLED BAG

KIM'S NEWSPAPER BAG -- ONE BAG FILLED PART WAY WITH THE REMAINING MATERIAL AT THE END FOLDED OVER

BREAD BAG W/O TWISTIE -- SPIN EXCESS MATERIAL AT END, OPEN END AND FOLD OVER FILLED BAG

CHIP CLIP/ CLOTHESPIN -- CLAMP END OF BAG SHUT

RUBBER BAND -- WRAP FLEXIBLE BAND ONE OR MORE TIMES AROUND END OF BAG

TWISTIE -- a) COMMON BREAD BAG TYPE (WIRE INSIDE PAPER)-WRAP AROUND TOP AND TWIST TOGETHER
b) OTHER BREAD BAG TYPE (PLASTIC THING)-FIT AROUND TOP OF BAG
c) GARBAGE BAG HOLDER-PLASTIC STRAP WITH SPIKED EDGES THAT CATCH WHEN PULLED THROUGH OPENING AT OPPOSITE END

STAPLES -- COMMON STAPLES BUT USING AN ALTERNATIVE MATERIAL

70'S HAIR PIN -- SHOOT A THIN ROD THROUGH BAG (LIKE A SKEWER)

POLARIZED METALLIC THREAD -- METALLIC THREAD WOVEN ONLY THROUGH THE OPEN END OF THE BAG WILL BE POLARIZED (ONE SIDE POSITIVE AND THE OTHER NEGATIVE) AND USE THE MAGNETIC ATTRACTION BETWEEN THE TWO SIDES TO KEEP THE BAG SHUT

FIBER ENTANGLEMENT -- COMBING OUT CURLY FIBERS ALLOWS ENTANGLEMENT DURING RECURL

WARP FIBERS -- USE EXTRA LENGTHS OF WARP FIBERS AT OPEN END OF BAG TO BE GRIPPED FOR CLOSING INSTEAD OF WOVEN FABRIC

PRICE TAG HOLDER -- SHOOT PRICE TAG HOLDER THROUGH ACCORDION PLEATS AT TOP OF BAG (SIMILAR TO 70'S HAIR PIN)

COLD SEAL -- a) ALREADY ON BAG i.e., DOUBLE-FACED TAPE PRINCIPLE
b) ADHESIVE IN MACHINE, TO BE PUT ON BAG

VELCRO -- SELF SEALING

ZIPPER -- ONE END ATTACHED, MECHANICALLY OPEN/SHUT

BASEBALL CAP -- PUSH SMALL DIAMETER HOLE OVER PIN FOR TIGHT FIT

TWISTING RING CLOSURE -- SLIDE RING OVER TOP OF BAG, TWIST TO CLOSE, SECURE IN PLACE WITH VELCRO (SIMILAR TO FOLD OVER BREAD BAG)

Fastening Alternatives Matrix

	A	B	C	D	E	F	G
1		Applicable to	Short Term	Temperature	M/C Degrees	Leakage	Fastener
2	**FASTENERS:**	Machine Design	Reliability	Limitations	Freedom Req'd	Rate	Mass
3							
4	Ziplock	Y	Good	Yes	Low	Low	Low
5	Heat Seal	N	-	Yes	-	-	None
6	Tie	Y	Good	No	Low	Low	Low
7	Drawstring	Y	Good	No	Low	Low	Low
8	Coin Purse	Y	Good	No	Low	Low	Medium
9	Shrink Wrap	N	-	-	-	-	Low/None
10	Buckle	N	-	-	Many	-	High
11	Snap	Y	Good	No	Low	Medium	Medium
12	Buttons	N	-	-	High	-	Medium
13	Crushed Metal Disc	Y	Good	No	Medium	Low	High
14	Stitch	Y	Good	No	Low	Low	Low
15	Phil's Newspaper	Y	Good	No	Medium	Low	Medium
16	Kim's Newspaper	N	Poor	-	-	Med/High	Low/Med
17	Foldover Bread Bag	N	-	-	-	-	Low/Med
18	Chip Clip	Y	Good	No	Low	Low	Med/High
19	Rubber Band	Y	Fair	Yes	High	Low/Med	Low
20	Twistie	Y	Good	No	Medium	Low	Low/Med
21	Plastic Bread Bag thing	Y	Good	Yes	Low	Low	Low
22	Garbage Bag Closure	Y	Good	Yes	Low/Med	Low	Low
23	Staples	Y	Fair	Yes	Low	Med/High	Medium
24	70's Hairpin	Y	Fair	No	Low	High	Low/Med
25	**Magnetic Closure**	**Y**	**Good**	**No**	**Low**	**Low**	**Low**
26	Fiber Entanglement	Y	Fair	No	Low	Medium	Low
27	Warp Fibers	Y	Fair	No	Low	Medium	Low
28	Price Tag Holder	N	-	Yes	-	Med/High	Low
29	Cold Seal (Adhesive)	Y	Good	No	Low	Low	Low
30	Velcro	Y	Good	Yes	Low	Low	Low/Med
31	Zipper	N	-	No	Low	Low	Med/High
32	Baseball Cap	Y	Fair	Yes	High	Medium	Low/Med
33	Twisting Ring Closure	Y	Good	No	Medium	Low	Medium

	H	I	J
1		Material	Long Term
2	**FASTENERS:**	Limitation	Reliability
3			
4	Ziplock	Resist radiation	-
5	Heat Seal	-	-
6	Tie	No	Good
7	Drawstring	No	Fair
8	Coin Purse	Maybe	Poor
9	Shrink Wrap	-	-
10	Buckle	-	-
11	Snap	Metal	Fair
12	Buttons	-	-
13	Crushed Metal Disc	Metal	Good
14	Stitch	No	Good
15	Phil's Newspaper	No	Fair
16	Kim's Newspaper	No	-
17	Foldover Bread Bag	No	-
18	Chip Clip	Metal/spring	Fair
19	Rubber Band	Rubber softens	Poor
20	Twistie	Metal	Good
21	Plastic Bread Bag thing	Plastic degrades	-
22	Garbage Bag Closure	Resist radiation	-
23	Staples	Req's puncture	-
24	70's Hairpin	Req's puncture	-
25	**Magnetic Closure**	**Metallic thread**	**Good**
26	Fiber Entanglement	No	Poor
27	Warp Fibers	No	Poor
28	Price Tag Holder	Req's puncture	-
29	Cold Seal (Adhesive)	Resist radiation	Poor
30	Velcro	Resist radiation	Poor
31	Zipper	Metal	Fair
32	Baseball Cap	Resist radiation	Poor
33	Twisting Ring Closure	can't use velcro	Fair

APPENDIX H

Machine Characteristics, Cost, and Production Calculations

Machine Characteristics, Production and Cost Calculations

1) Dimensions of habitat's surface (half-cylinder): diam = 9 m.
length = 12 m

2) Thickness of protective area: th = 2 m.

3) Total volume of dirt and bags needed for protection:

Vt = (pi/8) * [(9+2+2)^2-9^2]*12 Vt = 418 m^3
(estimate Vt to be 450 m^3) Vt = 450 m^3

4) Volume of dirt and bag (per filled bag): Vb= 29741 in^3
or Vb= .487 m^3

5) Number of bags:

Nb = 450 m^3/ .487 m^3 Nb = 924 bags

6) Total weight of bags (on earth):

Wb = Nb * wb
Wb = 924 bags * 1.50 lbs/bag Wb = 1386 lbs
or Wb = 628 kg

7) Velocity of truck: 7 km/hr

8) Width of bag when opened into rectangular shape: 75 cm.

9) Distance scoop is pushed into ground 3 cm.

10) Volume of dirt picked up per hour:

Vh = width * depth * velocity
Vh = 75 cm.*3 cm.*700000 cm/hr = 158 m^3/hr

11) Time for each bag to fill up (filling time alone):

Tb = Vb / Vh * 60 min/hr
Tb = 29702 in^3*(.0254m./in.)^3/158 m^3/hr*60 min/hr

Tb = .18 min.

Calculations (cont'd)

12) Total time to fill each bag:

(includes opening, moving, and closing), approx. Tt = 6 min.

13) Bags filled per day (8 hrs)

Bd = 8 hrs * 60 min/hr / Tt Bd = 80

14) Distance truck travels for each bag to fill up:

Dt = velocity * Tt
Dt = 7 km/hr * 1/60 hr/min * 6 min. Dt = 700 m.

15) Maximum number of bags on platform:

Nbp = bags filled per day Nbp = 80

16) Total length of bags on platform:

Lbt = bag length + Nbp*seam width
Lbt = 6 feet + 80*1 inch Lbt = 12.7 ft.
or Lbt = 3.86 m.

17) Length of platform:

Lp = bag length + Lbt + 2 in.
Lp = 6 ft. + 12.7 ft. + 1/6 ft. Lp = 18.9 ft.
or Lp = 5.75 m.

18) Width of platform:

wp = bag width wp = .914 m.

19) Thickness of platform: Tp = .2 cm.

20) Dimensions of tubing supporting platform: 16 x 2 mm * 1 m.
(Shigley, p.734)

21) Density of Aluminum 6061-T6 2700 kg/m^3
(Marks', 6-11)

Calculations (cont'd)

22) Weight of platform and tubing:

Wpt = 4*weight of tube + density*Lp*wp*Tp =
4*.687 kg. + 2700 kg/m^3* 5.75m* .914m *.002m.

Wpt = <u>31.1 kg.</u>

23) Weight of scoop:

support column -- 34 cm * 5 cm * .4 cm * 2.7 g/cm^3
= .184 kg

triangular sides -- 76.2 cm*5cm*.4cm *2.7g/cm^3 * (2)
= .823 kg

bottom -- [76.2cm*5cm*.4cm + (pi/8)*(73 cm)^2]*2.7 g/cm^3
= 6.06 kg

electromagnet -- = .5 kg

hooks -- negligible

rod / elevating hooks -- (100cm + 76.2cm) * (pi/4)*(1.2 cm)^2 * 2.7 g/cm^3
= .540 kg

Total weight of scoop: = <u>8.11 kg</u>

24) Total weight of scoop, platform, and bags
(excluding motors, microprocessors)
= 667 kg

25) Approximate weight of motors and microprocessors = 20 kg

26) Total weight of cargo to be shipped to the moon = **687 kg**

27) Cost of shipping this weight at $20,000/lb

$20,000/lb *1kg/2.204 lb * 687 kg = **$6.23 million**